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Dr. E. Geraniotis

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University of Maryland
Department of Electrical Engineering
College Park, MD 20742

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A summary of the results obtained in research sponosred by the Office of Naval Research under Contract N00014-89-J-1375 and conducted during the period December 1, 1988 to November 30, 1991 is presented. This research investigated several problems in the areas of spread-spectrum multiple-access techniques for satellite and mobile radio networks, multiple-access techniques for optical networks; and distribution detection estimation and data fusion in the presence of statistical uncertainty and correlated observations.

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Final Report

MULTIPLE-ACCESS TECHNIQUES FOR BROADBAND NETWORKS

For the period December 1, 1988 - November 30, 1991

Evaggelos Geraniotis

Department of Electrical Engineering
University of Maryland
College Park, MD 20742

This work was supported by the Office of Naval Research
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TABLE OF CONTENTS

ABSTRACT

A summary of the results obtained in research sponsored by the Office of Naval Research under Contract N00014-89-J-1375 and conducted during the period December 1, 1988 to November 30, 1991 is presented. This research investigated several problems in the areas of spread-spectrum multiple-access techniques for satellite and mobile radio networks; multiple-access techniques for optical networks; and distributed detection, estimation, and data fusion in the presence of statistical uncertainty and correlated observations.

1. SUMMARY OF RESEARCH

During the nearly three years of the research effort supported by the Office of Naval Research under contract N00014-89-J-1375, work was carried out in the following five areas:

(i) Spread-Spectrum Multiple-Access Techniques for Satellite and Mobile Radio Networks

(ii) Multiple-Access Techniques for Optical Networks

(iii) Distributed Detection and Data Fusion in the Presence of Statistical Uncertainty and Correlated Observations.

In the first area, we evaluated the performance of spread-spectrum multiple-access systems for use in satellite and mobile radio (including cellular) communications. Among the issues studied were the broadcast capability of direct-sequence and hybrid spread spectrum for satellite and mobile radio communications; the accurate assessment of the effect of unequal power levels for frequency-hopped, direct-sequence, and hybrid spread-spectrum cellular communications; the exact evaluation of the probability of capture and of multiple simultaneous receptions in spread-spectrum systems for the purpose of incorporating them into the analysis of network protocols; and the developement and performance evaluation of multi-access strategies for integrated voice/data code-division multiple-access (CDMA) radio networks.

In the second area, we provided the first accurate analysis of coherent random-carrier (RC) CDMA schemes recently introduced for use in high-capacity optical networks; accurate modeling of phase noise and other-user interference in such systems was carried out. The performance of coherent dense wavelength-division multiple-access (WDMA) schemes was accurately analyzed in the same context. Moreover, comparisons of WDMA and hybrid of WDMA and CDMA were carried out for high-capacity optical networks.

In the third area, we derived and analyzed algorithms for robust (optimal minimax) data fusion for multi-sensor detection systems; distributed multi-sensor parameter estimation in dependent noise; robust quantization and fusion in multi-sensor systems for the detection of weak signals in dependent noise; and quantization and fusion for multi-sensor discrimination for dependent observations.

A detailed description of the progress made in each one of the above areas is presented in the Sections 2.1-2.3. A list of the publications supported by the ONR contract, as well as of related publications, is provided in Section 3. The papers in that list serve as references for Sections 2.1-2.3. Finally, in Section 4 a list of the Theses and Dissertations supported by or related to the ONR contract is provided.

2. DETAILED PROGRESS REPORT

2.1 Spread-Spectrum Multiple-Access Techniques for Satellite and Mobile Radio Networks

Objective

Our objective was to evaluate accurately the capability of spread-spectrum signaling techniques (direct-sequence, frequency-hopping, and hybrid) for use in satellite, mobile radio, and cellular communication systems. The interface with network protocols (vertical, multi-layer integration) also had to be assessed. Issues of the integration of voice and data traffic had to be addressed.

Accomplishments

In [2] we studied in detail the broadcast capability of direct-sequence and hybrid spread spectrum for satellite and mobile radio communications; this work has established the theoretical basis for the use of spread spectrum in broadcast and multicast systems and finds applications in personal communication networks.

In [11] and [9], we provided the most accurate to date assessment of the effect of unequal power levels to the performance of frequency-hopped, direct-sequence, and hybrid spread-spectrum cellular communications. It was quantitatively established that the rule-of-thumb that frequency-hopped systems suffer less from the near-far problem than direct-sequence systems do is correct, but, at the same time, frequency-hopped signals also suffer and have a smaller multiple-access capability than what is theoretically attainable. Actually, we have shown that the multiple-access capability of frequency-hopped systems is larger than previously thought. Moreover, in [18] we analyzed multi-hop cellular radio networks employing frequency hopping.

In [7], we carried out the exact evaluation of the probability of capture and the rejection of primary other-user interference (i.e., when different users use the same signature sequence) for direct-sequence, frequency-hopped, and hybrid spread-spectrum systems. Moreover, in [10] we provided the exact evaluation of the probabilities of multiple simultaneous correct/incorrect receptions in frequency-hopped spread-spectrum systems as well as a time-efficient approximation which is valid for a broad range of system parameters. These results are extremely useful for the design and analysis of spread-spectrum radio networks, because they enable the (vertical) integration of the physical, data-link, and network layers of the OSI model by incorporating the probabilities of capture and multiple simultaneous correct receptions into the analysis of network protocols.

In [21], we developed multiple-access strategies for integrating efficiently voice and data traffic in CDMA packet radio networks. Our protocol uses a movable boundary in the code domain; it accommodates several voice calls simultaneously, while the data users contend for the remaining (if any) multiple-access capability of the CDMA channel. This innovative scheme finds applications in both terrestrial (packet radio or cellular) and satellite (mobile radio) applications. Extensions of this multiple-access scheme to mixed-media (HF, UHF, and EHF SATCOM channels) and

hybrid (terrestrial/satellite) networks with integrated voice and data traffic are currently under investigation.

2.2 Multiple-Access Techniques for Optical Networks

Objective

Our objective was to analyze and design signaling schemes and network protocols for optical communications. Our emphasis was placed on the accurate modeling of phase noise and other-user interference in optical multiple-access schemes that employ coherent detection techniques.

Accomplishments

In [22], we provided the first accurate analysis of coherent random-carrier (RC) CDMA schemes recently introduced for use in high-capacity optical networks. In this scheme, coherent optical techniques are employed to exploit the huge bandwidth available in single-mode optical fibers and are coupled with spread-spectrum direct-sequence modulation in order to mitigate the interference from other signals (in-band other-user interference) due to the frequency overlap caused by the instability of the carrier frequency of the laser, or to potential mistakes in frequency coordination and assignment. In our work, accurate modeling of phase noise and other-user interference in such systems was carried out. To evaluate accurately the average bit-error probability of RC CDMA scheme, we employed the characteristic-function of the other-user interference at the output of the optical matched filter. Our evaluation method allowed the analysis and comparison of binary phased-shift-keying (BPSK) and on-off-keying (OOK) data modulation schemes. .Schemes with time-synchronous or asynchronous users were analyzed. The analysis was carried out for arbitrary values of the CDMA spreading gain and number of interfering users, whereas the overall optical fiber bandwidth remained fixed.

In [27], we extended and completed the work of [22] by analyzing accurately the performance of two more optical multiple-access schemes that are candidates for use in high-capacity optical networks: wavelength-division multiple-access (WDMA) schemes and hybrids of WDMA and CDMA. WDMA schemes appear very promising for providing maximum bandwidth utilization efficiency in high-capacity optical networks. However, the instability of the laser's carrier frequency may cause frequency overlaps of neighboring signals and may degrade the bandwidth utilization efficiency. The use of CDMA, together with WDMA, can mitigate the other-user interference effects and restorethe desirable efficiency. In our work, we first analyze accurately the performance of pure WDMA schemes with coherent detection in the presence of phase noise and other-user interference. The characteristic-function technique was used in this context. BPSK and OOK data modulation schemes were considered, as well as scenarios with time-synchronous or asynchronous users. These results provide the first accurate evaluation of dense WDMA schemes. Moreover, our analytical techniques have enabled the evaluation of the performance of hybrid WDMA and CDMA schemes and their comparison with pure WDMA schemes. It has been shown that for a fixed optical-fiber bandwidth and number of simultaneous users hybrid

WDMA/CDMA schemes outperform pure WDMA schemes for a substantial range of the system parameters.

We have also initiated work on protocols for video, voice, and data integration in optical multiple-access networks. The schemes under consideration involve fixed-leght frames with two movable boundaries. The video and voice users make their schedules in advance by using a preassigned slot. The first portion of the frame is assigned to the variable-rate video users, while the variable-rate voice users occupy the last portion of the frame. Data packets fill up the remaining slots between these two movable boundaries in a random-access contention resolution fashion. The protocol is optimized with respect to blocking probabilities for voice and video, packet dropping probability for video, and average delay for data. Most of this work was carried out during B. Ghaffari's (see Section 4) Ph.D. dissertation and will result in a publication that is currently under preparation.

2.3 Distributed Detection and Data Fusion in the Presence of Statistical Uncertainty and Hostile Interference

Objective

Our objective was to derive and analyze reliable and time-efficient schemes for the distributed detection, estimation, and data fusion of arbitrary signals from multiple sensors in environments characterized by correlated sensor observations and uncertainty in the statistics of the dependent noise. Emphasis was placed on robust such schemes that are easy to implement.

Accomplishments

In [4], we derived optimal minimax robust data fusion schemes for multi-sensor detection schemes. The sensor observations were modeled as i.i.d. random variables with probability distributions only known to belong to uncertainty classes determined by two-alternating Choquet capacities. Optimal schemes for the cases of large number of sensors and of large number of times the fusion center collects the sensor decisions were derived.

In [8], the problem of the distributed of a weak non-random location parameter in additive stationary dependent noise (according to m-dependent, ϕ-mixing, and ρ-mixing models) was addressed. Suboptimal M-estimates employing memoryless nonlinearities were employed by each sensor. The nonlinearities were selected to optimize suitable performance measures that coupled the estimation procedure of the multiple sensors. This optimization resulted in having to solve linear integral equations involving the sensor nonlinearities. For an m-dependent Gauchy noise paradigm we have established that our multi-sensor estimation schemes outperform the ones that ignore dependence in sensor observations.

In [24] and [26], several quantization and data fusion schemes based on memoryless sensor nonlinearities were optimized and their performance was evaluated. In those schemes, different amounts of information (binary sensor decisions, non-binary quantized sensor decisions, quantized sensor observations, or unquantized sensor test

statistics) are passed from the sensors to the fusion center and are combined according to several fusion rules. The sensor nonlinearities and the coefficients of the fusion rules are optimized with respect to suitable performance measures. Again, linear integral equations are solved to obtain the optimal nonlinearities. Comparisons of the performance of our schemes to the ones that ignore dependence in sensor observations establish the superiority of the former. Similarly, in [25], similar results are obtained for multi-sensor discrimination between two arbitrary m-dependent or ρ-mixing time-series obserbed by multiple sensors.

3. LIST OF PUBLICATIONS SUPPORTED BY THE ONR CONTRACT

Papers Appeared or Accepted for Publication in Journals (ONR Support)

1. E. Geraniotis. "Robust Matched Filters for Noise Uncertainty within Two Alternating Capacity Classes." *IEEE Transactions on Information Theory,* Vol. IT-36, pp. 426-429, March 1990.

2. E. Geraniotis and B. Ghaffari. "Broadcast Capability of Direct Sequence and Hybrid Spread Spectrum." Special Issue on Spread-Spectrum Communications of the *IEEE Journal on Selected Areas in Communications,* Vol. JSAC-8, pp. 489-502, May 1990.

3. E. Geraniotis. "Effect of Worst-Case Multiple Partial-Band Noise and Tone Jammers on Coded FH/SSMA Systems." Special Issue on Spread-Spectrum Communications of the *IEEE Journal on Selected Areas in Communications,* Vol. JSAC-8, pp. 613-627, May 1990.

4. E. Geraniotis and Y. A. Chau. "Robust Data Fusion for Multisensor Detection Systems." *IEEE Transactions on Information Theory,* Vol. IT-36, pp. 1265-1279, November 1990.

5. E. Geraniotis and B. Ghaffari. "Performance of Binary and Quaternary Direct-Sequence Spread-Spectrum Multiple-Access Communications with Random Signature Sequences." *IEEE Transactions on Communications,* Vol. COM-39, pp. 713-724, May 1991.

6. T. Vlachos and E. Geraniotis. "Performance Study of Hybrid Spread-Spectrum Random-Access Communications." *IEEE Transactions on Communications,* Vol. COM-39, pp. 975-985, June 1991.

7. M. Soroushnejad and E. Geraniotis. "Probability of Capture and Rejection of Primary Multiple-Access Interference in Spread-Spectrum Networks." *IEEE Transactions on Communications,* Vol. COM-39, pp. 986-994, June 1991.

8. Y. A. Chau and E. Geraniotis. "Distributed Multisensor Parameter Estimation in Dependent Noise." *IEEE Transactions on Communications,* Vol. COM-40, pp. 373-384, February 1992.

9. M. Soroushnejad and E. Geraniotis. "Performance Comparison of Different Spread-Spectrum Signaling Schemes for Cellular Mobile Radio Networks." *IEEE Transactions on Communications,* Vol. COM-40, pp. 947-956, May 1992.

Appeared or Accepted Related Papers (No ONR Support)

10. T. Ketseoglou and E. Geraniotis. "Multireception Probabilities for FH/SSMA Communications." *IEEE Transactions on Communications*, pp. 223-233, Vol. COM-40, January 1992.

11. E. Geraniotis. "Multiple-Access Capability of Frequency-Hopped Spread-Spectrum Revisited: An Exact Analysis of the Effect of Unequal Power Levels." *IEEE Transactions on Communications*, Vol. COM-38, pp. 1066-1077, July 1990.

12. W. E. Snelling and E. Geraniotis. "Sequential Detection of Unknown Frequency-Hopped Waveforms." Special Issue on Secure Communications of the *IEEE Journal on Selected Areas in Communications*, Vol. JSAC-7, pp. 602-617, May 1989.

13. J. F. Kuehls and E. Geraniotis. "Presence Detection of Phase-Shift-Keyed and Direct-Sequence Signals Using a Prefilter-Delay-and-Multiply Device." Special Issue on Spread-Spectrum Communications of the *IEEE Journal on Selected Areas in Communications*, Vol. JSAC-8, pp. 915-933, June 1990.

14. D. Sauder and E. Geraniotis. "Optimal and Robust Memoryless Discrimination from Dependent Observations." *IEEE Transactions on Information Theory*, Vol. IT-37, pp. 73-91, January 1991.

15. L. Nemsick and E. Geraniotis. "Adaptive Multichannel Detection of Frequency-Hopping Signals." *IEEE Transactions on Communications*, pp. 1502-1511, Vol. COM-40, September 1992.

16. W. E. Snelling and E. Geraniotis. "Analysis of Compressive Receivers for the Optimal Interception of Frequency-Hopped Waveforms." Accepted for publication in the *IEEE Transactions on Communications*, to appear in 1993.

17. D. Sauder and E. Geraniotis. "One-Step Memory Nonlinearities for Signal Detection and Discrimination from Correlated Observations." Accepted for publication in the *IEEE Transactions on Information Theory*, to appear in 1993.

Papers Submitted for Publication and Still under Review (ONR Support)

18. J. W. Gluck and E. Geraniotis. "Performance of Cellular Frequency-Hopped Spread-Spectrum Radio Networks." Submitted to the *IEEE Transactions on Vehicular Communications*, 1991, under review.

19. E. Geraniotis. "Sequential Tests for Memoryless Discrimination from Dependent Observations--Part I: Optimal Tests." Submitted to the *IEEE Transactions on Information Theory,* 1991, under review.

20. E. Geraniotis. "Robust Sequential Tests for Memoryless Discrimination from Dependent Observations." Submitted to the *IEEE Transactions on Information Theory,* 1991, under review.

21. M. Soroushnejad and E. Geraniotis. "Multi-Access Strategies for an Integrated Voice/Data CDMA Packet Radio Network." Submitted for publication to the *IEEE Transactions on Communications,* 1990, under review.

22. G. Ghaffari and E. Geraniotis. "Analysis of Coherent Random-Carrier Code-Division Multiple Access for High-Capacity Optical Networks." Submitted for publication to the *IEEE Transactions on Communications,* 1990, under review.

23. Y. A. Chau and E. Geraniotis. "Distributed Detection from Multiple Sensors with Correlated Observations." Submitted to the *IEEE Transactions on Automatic Control,* 1990, under review.

24. Y. A. Chau and E. Geraniotis. "Quantization and Fusion in Multi-Sensor Systems for the Detection of Weak Signals." Submitted to the *IEEE Transactions on Information Theory,* 1990, under review.

25. Y. A. Chau and E. Geraniotis. "Quantization and Fusion for Multi-Sensor Discrimination from Dependent Observations." Submitted to the *IEEE Transactions on Aerospace and Electronic Systems,* 1990, under review.

26. Y. A. Chau and E. Geraniotis. "Multi-Sensor Correlation and Quantization in Distributed Detection Systems." Submitted to the *IEEE Transactions on Signal Processing,* 1990, under review.

27. G. Ghaffari and E. Geraniotis. "Comparison of Coherent WDMA and Hybrid WDMA/CDMA for the Multiplexing of Optical Signals." Submitted to the *IEEE Transactions on Lightwave Technology,* 1991, under review.

28. E. Geraniotis. "Robust Distributed Discrete-Time Block and Sequential Detection in Uncertain Environments." Submitted to the *IEEE Transactions on Communications,* 1991, under review.

Submitted Related Papers (No ONR Support)

29. D. Sauder and E. Geraniotis. "Signal Detection Games with Power Constraints." Submitted for publication in the *IEEE Transactions on Information Theory,* to appear in 1993.

30. W. E. Snelling and E. Geraniotis. "The Interception of Spread-Spectrum Waveforms with the Amplitude Distribution Function." Submitted to the *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 1991, under review.

31. J. F. Kuehls and E. Geraniotis. "Memoryless Locally Optimum Detection of Chip Rate Lines of DS/SS Signals." Submitted to the *IEEE Transactions on Acoustics, Speech, and Signal Processing,* 1991, under review.

32. J. Haimerl and E. Geraniotis. "Neural Networks for the Sequential Discrimination Radar Targets." Submitted to the *EEE Transactions on Neural Networks*, 1991, under review.

Papers in Conference Proceedings

1. E. Geraniotis and Y. A. Chau. "Distributed Detection of Weak Signals from Multiple Sensors with Correlated Observations." *Proceedings of the Twenty-Seventh Conference on Decision and Control,* pp. 2501-2506, Austin, TX, December 1988 (invited paper).

2. D. Sauder and E. Geraniotis. "Optimal and Robust Discrimination under an SNR-Type Performance Measure." Presented at the *1989 Conference on Information Sciences and Systems,* Johns Hopkins University, March 1989.

3. Y. A. Chau and E. Geraniotis. "Distributed Estimation of a Location Papameter in Dependent Noise." Presented at the *1989 Conference on Information Sciences and Systems,* Johns Hopkins University, March 1989.

4. M. Soroushnejad and E. Geraniotis. "Voice/Data Integration in Random-Access Code-Division Multiple-Access Packet Radio Networks." *Proceedings of the 1989 Conference on Information Sciences and Systems,* pp. 706-710, Johns Hopkins University, March 1989.

5. E. Geraniotis and Y. A. Chau. "Distributed Discrimination from Correlated Sensor Observations." *Proceedings of the 1989 IEEE American Control Conference,* vol. 2, pp. 1304-1308, Pittsburgh, PA, June 1989 (invited paper).

6. E. Geraniotis and Y. A. Chau. "Data Fusion in Multiple Sensor Systems for the Detection of Weak Signals." *Proceedings of the 1989 Symposium on Command and Control Research,* pp. 359-364, Washington, DC, June 1989.

7. J. F. Kuehls and E. Geraniotis. "A Technique for Detecting Unknown Weak Signals in Noise That Is Not Additive White Gaussian." *1989 IEEE Military Communications Conference,* Conference Record, Vol. 2, pp. 19.7.1-7, Boston, MA, October 1989.

8. Y. A. Chau and E. Geraniotis. "Asymptotically Optimal Quantization and Fusion in Multiple Sensor Systems." *Proceedings of the Twenty-Eighth Conference on Decision and Control,* pp. 585-587, Tampa, FL, December 1989.

9. B. Ghaffari and E. Geraniotis. "Analysis of Coherent Asynchronous Random-Carrier Code-Division Multiplexing for High-Capacity Optical Networks." *Abstracts of the 1990 IEEE International Symposium on Information Theory,* pp. 55-56, San Diego, CA, January 1990.

10. Y. A. Chau and E. Geraniotis. "Optimal Quantization and Fusion in Multiple Sensor Systems with Correlated Observations." *Abstracts of the 1990 IEEE International Symposium on Information Theory,* p. 35, San Diego, CA, January 1990.

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12. D. Sauder and E. Geraniotis, "Optimal One-Step Memory Nonlinearities for Signal Discrimination from Dependent Observations." Proceedings of the *1990 Conference on Information Sciences and Systems,* pp. 410-414, Princeton University, March 1990.

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15. W. E. Snelling and E. Geraniotis. "The Optimal Interception of Frequency-Hopped Waveforms via a Compressive Receiver." Proceedings of the 1990 *IEEE*

Military Communications Conference, pp. 38.4.1-8, Monterey, CA, October 1990.

16. Y. A. Chau and E. Geraniotis. "Multi-Sensor Correlation and Quantization for Distributed Detection Systems." *Proceedings of the Twenty-Ninth Conference on Decision and Control,* pp. 2692-2697, Honolulu, Hawaii, December 1990 (invited paper).

17. J. A. Haimerl and E. Geraniotis. "Neural Networks for Sequential Discrimination of Radar Targets." To be presented to the 1991 *IEEE 1991 National Radar Conference,* Los Angeles, CA, March 1991, to appear in the Conference Proceedings.

18. D. Sauder and E. Geraniotis. "Signal Detection Games with Power Constraints." Proceedings of the *1991 Conference on Information Sciences and Systems,* pp. 487-492, Johns Hopkins University, March 1991.

19. B. Ghaffari and E. Geraniotis. "Comparison of WDMA and Hybrid WDMA/CDMA for the Multiplexing of Optical Signals." Proceedings of the *1991 Conference on Information Sciences and Systems,* pp. 804-809, Johns Hopkins University, March 1991.

20. I.-H. Lin and E. Geraniotis. "Optimal Joint Voice Scheduling and Data Routing in Optical Networks by Iterative Methods." Proceedings of the *1991 Conference on Information Sciences and Systems,* pp. 417-422, Johns Hopkins University, March 1991.

21. D. Sauder and E. Geraniotis. "Models for Discrimination and Data Extrapolation of Positive-Valued Correlated Random Processes." *Proceedings of the 1991 IEEE International Symposium on Information Theory,* p. 171, Budapest, Hungary, June 1991.

22. B. Ghaffari and E. Geraniotis. "Multi-Media Integration in Multiple-Access Satellite Networks." *Proceedings of the 1991 IEEE International Symposium on Information Theory,* p. 210, Budapest, Hungary, June 1991.

23. W. E. Snelling and E. Geraniotis. "The Detection of Frequency-Hopped Waveforms via the Amplitude Distribution Function." Proceedings of the 1991 *IEEE Military Communications Conference,* pp. 24.3.1-6, Mc Lean, VA, October 1991.

24. Y. A. Chau and E. Geraniotis. "Data Fusion for Multi-Sensor Imaging Systems." Proceedings of the 1991 *IEEE Conference on Decision and Control,* pp. 2631-2632, Brighton, England, UK, December 1991.

25. L. W. Nemsick and E. Geraniotis. "Adaptive Channelized Interception of Frequency Hopping Signals." Proceedings of the *1992 IEEE Military Communications Conference,* pp. 4.3.1-4.3.7, San Diego, CA, October 1992 (invited paper).

26. E. Geraniotis, M. Soroushnejad, and W.-B. Yang. "A CDMA/Framed-ALOHA Protocol for Voice/Data Integration in Hybrid (Satellite/Terrestrial) Networks." Proceedings of the *1992 IEEE Military Communications Conference,* pp. 52.1.1-52.1.6, San Diego, CA, October 1992 (invited paper).

4. LIST OF THESES AND DISSERTATIONS SUPPORTED BY OR RELATED TO THE ONR CONTRACT

Ph.D. Theses Supervised

Completed

John Kuehls (graduated in December 1989). Thesis title: "On the Detection of Unknown Binary Phase-Shift-Keyed Waveforms via Their Rate Lines"

William Snelling (graduated in May 1990). Thesis title: "New Methods for the Detection and Interception of Unknown, Frequency-Hopped Waveforms"

Mohsen Soroushnejad (graduated in August 1990). Thesis title: "Packet Radio Networks in CDMA Environment: Capture, Channel-Access Protocols, and Voice/Data Integration"

Yawgeng A. Chau (graduated in December 1990). Thesis title: "Robust Distributed Detection, Quantization, and Data Fusion in Multi-Sensor Networks"

Behzad Ghaffari (graduated in August 1991). Dissertation title: "Multiple-Access Protocols and Data/Voice/Video Integration in High-Capacity Optical Networks"

Douglas Sauder (graduated in August 1992). Dissertation title: Non-Gaussian Methods for Signal Discrimination

In Progress

Vahid Ramezzani. Research area: Modulation and Coding Techniques for Atmospheric and Underwater Optical Communications

Wen-Bin Yang. Research area: Multiple-Access Protocols, Switching, and Routing for the Broadband ISDN (Integrated Services Digital Network)

Ie-Hong Lin. Research area: Multiple-Access Protocols and Routing for Integrated (Voice/Data/Video) Mixed-Media (Ground/Satellite) Packet Radio Networks

M.S. Theses Supervised

Completed

Larry Nemsick (graduated in December 1989). Thesis title: "Adaptive Multi-Channel Detection of Frequency Hopping Signals"

Joseph Haimerl (graduated in August 1990). Thesis title: "Comparison of Parametric and Nonparametric Schemes for Discrete-Time Discrimination"

Mike Lynch. (graduated in December 1992). Thesis title: "A Distributed Source Control for Multi-Media ATM Networks"

In Progress

Ahmad Kamal. Research area: Routing and Control of Integrated Video/Voice/Data Traffic in ATM Networks.

Stephen Balakirsky. Research area: Data Fusion Algorithms for Automatic Target Recognition.

Broadcast Capability of Direct Sequence and Hybrid Spread Spectrum

EVAGGELOS GERANIOTIS, SENIOR MEMBER, IEEE, AND BEHZAD GHAFFARI, STUDENT MEMBER, IEEE

Abstract—Two forms of spread-spectrum signaling: direct sequence and hybrid (direct sequence/frequency hopped) are shown to provide high broadcast capability, especially when used in conjunction with forward-error-control coding schemes. The *broadcast capability* is defined as the maximum number of *simultaneous distinct messages* that can be transmitted to distant receivers from a single transmitter at a given bit-error-rate. This quantity provides a useful measure of the capacity of hub-to-mobile or satellite-to-earth-station links of communication networks. When *bursty* data or voice traffic is dominant in such networks, the above forms of spread-spectrum code-division multiple-access (CDMA) provide a viable alternative to frequency-division (FDMA) or time-division (TDMA) multiple-access.

Different ways of multiplexing the direct-sequence and hybrid signals are presented which employ distinct carriers, distinct pairs of orthogonal carriers, and only two orthogonal carriers for broadcasting the different messages. Systems with chip-synchronous signals and systems with random delays between the signals are considered. The average error probability of all systems is evaluated using the characteristic-function and Gaussian-approximation techniques. Besides the uncoded systems, systems using Reed-Solomon and convolutional codes are analyzed. A comparison of the broadcast capability of the different schemes is presented.

I. Introduction

In the past ten years, spread-spectrum multiple-access (SSMA) systems have received considerable attention in the literature (see [1]-[14], which in no way constitute an exhaustive list). Besides the properties of low detectability (LPI), antijam resistance, and privacy, which are especially desirable in military multiple-access systems, SSMA offers simultaneous channel access without the need for time coordination between the different users, low peak-to-average power ratio (desirable for bursty traffic situations) and resistance to frequency-selective and multipath fading. These properties of SSMA are of interest to commercial multiple-access systems like the mobile satellite systems (MSAT) and the very small aperture terminal satellite systems (VSAT).

Two modes of operation of SSMA have attracted most attention: the *interference channel mode* (several point-to-point or paired transmissions, see [1]-[10]), in which each receiver despreads and demodulates one of the transmitted signals using distinct spread-spectrum codes without any cooperation from other receivers; and the *multiple-access mode* (multipoint-to-point), in which several stations communicate with a single receiver, which employs matched filters to despread and demodulate all or some of the transmitted signals either separately (suboptimal multireceiver, see [11]-[12]), or with some degree of cooperation between the different matched filters (optimal or near-optimal multireceiver, see [13]-[14]). In both cases, the *multiple-access capability* of the spread-spectrum system is defined as the maximum number of simultaneous distinct transmitted signals from independent stations that can be tolerated in the neighborhood of a single or multiple receiver, so that the error probability for the reception of a particular signal does not exceed a prespecified maximum value.

By contrast, the *broadcast mode* of operation, in which several distinct messages or a common message are transmitted simultaneously from a single station to different receivers, has not received sufficient attention. In our conference paper (see [15]), we introduced broadcast direct-sequence (DS) spread-spectrum systems and presented some preliminary results. In this paper, we examine several alternatives of broadcast spread-spectrum systems and evaluate their *broadcast capability*, defined as the maximum number of *simultaneous distinct messages* that can be transmitted to distant receivers from a single station at a given received bit-error-rate. This quantity provides a useful measure of the capacity of hub-to-mobile or satellite-to-earth-station links in communication networks such as the MSAT and the VSAT. When *bursty* data or voice traffic is dominant in such networks, the above forms of spread-spectrum CDMA provide a viable alternative to FDMA or TDMA multiple access.

The system configurations described in our paper rely on minimum synchronization and coordination requirements; the users do not know each other's sequences and are not necessarily time-synchronous; the central station knows the identities of all users; each receiver monitors continuously his signature sequence in anticipation of messages transmitted to it. Besides the less strigent requirements on time coordination, there are several other advantages in using CDMA instead of TDMA or FDMA in the mobile satellite environment. These include 1) the use of spread-spectrum with two antennae polarizations (instead of only one that can be used with FDMA) be-

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Effect of Worst Case Multiple Partial-Band Noise and Tone Jammers on Coded FH/SSMA Systems

EVAGGELOS GERANIOTIS, SENIOR MEMBER, IEEE

Abstract—In this paper, we characterize and evaluate the effect of simultaneous multiple partial-band noise or tone jammers and other user interference on a single communication link employing frequency-hopped spread-spectrum (FH/SS) signaling, *M*-ary frequency shift keying (FSK) modulation with noncoherent demodulation, and Reed-Solomon coding. For the symbol error probability of these systems, we derive exact expressions in the absence of multiple-access (MA) interference and tight upper bounds in the presence of other-user interference. Although our analytical methods are valid for any number of multiple jammers, we restrict our numerical study to the cases of two and three partial-band noise and tone jammers.

For fixed values of the spectral densities of noise jammers, or the energies per symbol of tone jammers, we evaluate the worst case fraction of the band that each jammer should use in order to maximize the error probability of the FH/SS or FH/SSMA system. For the range of the signal-to-jammer power ratios examined, multiple noise or tone jammers appear to have no advantage over a single noise or tone jammer of equivalent spectral density or energy per symbol, but achieve approximately the same worst case performance by jamming smaller fractions of the band.

I. Introduction

THE effect of worst case partial-band noise and tone jamming on frequency hopped spread spectrum (FH/SS) has been thoroughly studied over the years. References [1]-[6] constitute a representative selection of works that describe FH/SS systems operating in the presence of a single partial-band noise or tone jammer. Moreover, worst case interference has been identified and several error-control schemes have been proposed for enabling the FH/SS systems to combat interference.

More recently, the combined effects of partial-band noise jamming, other-user interference [also termed multiple-access (MA) interference], Rician nonselective fading, and additive white Gaussian noise (AWGN) were studied in [8]. A common characteristic of the work described in [1]-[6] and [8] is that hostile interference consists either of a single unmodulated signal, which is hopped around the targeted frequency band, or of white noise generated in different subbands of the targeted frequency band. A single jamming device generates these signals.

In this paper, we characterize and evaluate the effect of simultaneous multiple partial-band noise or tone jammers and other-user interference on a single communication link employing FH/SS signaling, *M*-ary frequency shift keying (FSK) modulation with noncoherent demodulation, and Reed–Solomon coding. We develop techniques for the evaluation of the symbol error probability—also termed symbol error rate (SER)—of these systems. In particular, we derive 1) exact expressions and tight upper bounds for SER when multiple partial-band noise or tone jammers but no other-user interference are present, and 2) tight upper bounds on SER when both multiple noise or tone jammers and other-user interference are present. In the case of FH/SSMA systems, we can analyze accurately the effect of other-user interference with different power levels by extending the results of [9]. The expressions for SER can also serve as upper bounds for the bit error rate (BER).

Although our analytical methods are valid for an arbitrary number of jammers and interfering users, we restrict our numerical study to the cases of two and three multiple noise or tone jammers; the numerical study of FH/SSMA systems disturbed by a larger number of simultaneous jammers was prohibited by the excessive computations needed to evaluate the worst case allocation of fractions of the band jammed. There is no restriction on the number of interfering users. Numerical results are generated for both uncoded and Reed–Solomon coded FH/SS and FH/SSMA systems with errors-only decoding. When the spectral densities of the noise jammers or the energies per symbol of the tone jammers are fixed, we evaluate the optimal fraction of the band that each jammer should use in order to maximize the error probability of the FH/SSMA system; this corresponds to a worst case scenario from the communicator's standpoint. We also compare the performance of multiple noise (or tone) jammers to that of a single noise (or tone) jammer, whose spectral density (or energy per symbol) equals the sum of the spectral densities (or energies per symbol) of the multiple jammers. Finally, we compare the performance of noise and tone jammers and assess the effects of other-user interference on the worst case scenario.

The paper is organized as follows. Multiple partial-band noise jammers are treated in Section II where error probabilities are computed exactly (or bounded) for the single-user and multiuser cases in Sections II-A and B, respectively; this is repeated in Section III for multiple partial-band tone jammers. In both sections, the cases of two and

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The author is with the Department of Electrical Engineering and Systems Research Center, University of Maryland, College Park, MD 20742.

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Multiple-Access Capability of Frequency-Hopped Spread-Spectrum Revisited: An Analysis of the Effect of Unequal Power Levels

EVAGGELOS GERANIOTIS, SENIOR MEMBER, IEEE

Abstract—In this paper we present a new method for the evaluation of the probability of error of uncoded asynchronous frequency-hopped spread-spectrum multiple-access (FH/SSMA) communications. For systems with binary FSK modulation our method provides an accurate approximation and a tight upper bound to the bit error probability; for systems with M-ary FSK modulation, it provides tight upper bounds to the symbol error probability. The method enables the computationally efficient averaging of the error probability with respect to the delays, phase angles, and data streams of the different users. It relies on the integration of the product of the characteristic function of the envelope of the branch of the BFSK demodulator, which carries the desired signal, and of the derivative of the characteristic function of the envelope of the other branch. For sufficient frequency separation between the BFSK tones, the new method can achieve any desirable accuracy. Moreover, the computational effort required for its evaluation grows linearly with the number of interfering users. In the M-ary case, tight upper bounds based on the union bound and the results of the binary case are derived.

The new method allows us to quantify accurately the effect of unequal power levels on other-user interference in FH/SSMA systems for the first time. Comparison of the multiple-access capability of FH/SS systems without error-control can support (at a given error rate) considerably many more simultaneous users than previously thought when the relative received powers of the users are not significantly different. This trend is amplified further for systems with error control. Our results indicate that the FH/SSMA systems also suffer from the near-far problem, although less seriously than direct-sequence SSMA systems.

I. Introduction and Problem Statement

PREVIOUS research on frequency-hopped spread-spectrum multiple-access systems (FH/SSMA) has not provided exact results on the average probability of error, primarily because of the difficulty in evaluating accurately the conditional probability of error, given that a number of interfering signals hit the desired signal. Due to the lack of accurate expressions for the error probability, the effect of unequal power levels of the interfering users—termed the near-far problem in the context of direct-sequence spread-spectrum (DS/SS) systems—has not been studied. In this paper, we remedy this situation by deriving accurate approximations and tight upper bounds on the bit (and symbol) error probabilities of the FH/SSMA systems that take into consideration the effect of unequal power levels of the interfering signals. In the following, we present a brief review of the existing results and identify the difficulties encountered in the evaluation of the error probabilities for FH/SSMA systems.

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The author is with the Department of Electrical Engineering and Systems Research Center, University of Maryland, College Park, MD 20742.

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In the performance of FH/SSMA and hybrid FH-DS/SSMA systems with M-ary FSK modulation and noncoherent demodulation $\bar{P}_e(K)$, the probability of a symbol error, given that K other users share the same channel with the user under consideration (desired signal), plays a seminal role. This probability is evaluated as follows; if $P_e(k)$ denotes the conditional probability of a symbol error when hits from k users occur and P_h the probability that any particular other user will hit a symbol of the desired signal, then $\bar{P}_e(K)$ is upper bounded by

$$\bar{P}_e(K) \leq \sum_{k=0}^{K} \binom{K}{k} P_h^k (1-P_h)^{K-k} P_e(k). \tag{1}$$

In (1), $P_e(k)$ actually denotes the probability of error when k full hits occur. We say that a **full hit** from an interfering signal occurs when the signal is present in the same frequency bin (slot) for the entire duration of the particular M-ary symbol. Similarly, a **partial hit** occurs when the interfering signal is present in the same frequency bin for part of the M-ary symbol's duration. The terms full and partial hits described above have been used in the relevant literature to mean exclusively hits that occur at the level of the frequency-hopping pattern. However, to evaluate the performance of FH/SSMA systems accurately, one has to distinguish between two levels of hits: those occurring at the frequency hopping level (on the frequency bins or slots used for frequency hopping) and those occurring at the level of the M-ary FSK tones (used for modulating the data); we name the former **FH hits** and the latter **tone hits** (refer to Fig. 1 for a pictorial representation of the various kinds of hits). The probability of an FH hit (full or partial) for an AWGN or a nonselective fading channel and random memoryless hopping patterns is given by [1] as $P_h = (1 + 1/N_s(1 - 1/q))1/q$, where N_s is the number of M-ary FSK symbols per dwell time and q the number of frequencies available for hopping. Therefore, (1) provides an upper bound, since it is assumed that all FH hits that occur with probability P_h are full FH hits.

Hard bounds and approximations on $P_e(k)$ are available in the existing literature. Specifically in [1], the conditional probability of error, given that k users cause full FH hits, was upper-bounded by 1 due to the difficulty of obtaining more accurate estimates of its value; in it, it was assumed that all (FH) hits resulted in symbol errors. Later in [2] and [3], a Gaussian-approximation technique was proposed for evaluating the $P_e(k)$ of coherent and noncoherent hybrid FH-DS/SSMA systems. If the number of chips per bit N is set to 1, these results provide approximations to $P_e(k)$ for FH/SSMA systems. For coherent systems, the accuracy of the Gaussian-approximation technique was checked via a more accurate characteristic-function technique. However, for noncoherent systems, the accuracy of the Gaussian-approximation technique was never validated by more accurate results, because there are not any.

Recently, in [9] an exact expression for the error probability was derived for orthogonal BFSK when there is one interfering user, but only simulation was used to evaluate the performance for the case of multiple interfering users.

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Performance of Binary and Quaternary Direct-Sequence Spread-Spectrum Multiple-Access Systems with Random Signature Sequences

Evaggelos Geraniotis, *Senior Member, IEEE*, and Behzad Ghaffari, *Student Member, IEEE*

***Abstract*—The performance of synchronous and asynchronous, binary and quaternary (with and without offset) direct-sequence spread-spectrum multiple-access communication systems employing random signature sequences and arbitrary chip waveforms is investigated. The average probability of error at the output of the correlation receiver is evaluated using a characteristic-function approach for all the above systems. Numerical results are presented that illustrate performance comparisons between systems employing random and deterministic signature sequences, synchronous and asynchronous systems, systems with rectangular or sinewave chip waveforms, and binary and quaternary systems with the same data rates and bandwidth. In all cases, the accuracy of the Gaussian approximation is also examined.**

I. Introduction

Direct-sequence spread-spectrum multiple-access (DS/SSMA) communication systems have received considerable attention in the past 10 years (see [1]–[10]). The performance of binary and quaternary DS/SSMA systems operating over additive white Gaussian (AWGN) channels has been investigated thoroughly both for the average signal-to-noise ratio (see [1]–[3]) and for the average error probability at the output of the correlation receiver (see [6]). Consequently, the results concerning deterministic signature consequences may be deemed complete. By contrast, for binary DS/SSMA asynchronous systems employing random signature sequences, the average signal-to-noise ratio at the output of the correlation receiver was evaluated in [1] and [4] and only recently bounds and approximations on the error probability were derived in [9]. In this paper, the characteristic function of the other-user interference for asynchronous binary DS/SSMA systems with random signature sequences was derived. However, our own work of [8] preceded [9] in the derivation of the characteristic function of other-user interference for such systems and the actual method of derivation was different than that of [9]. Before detailing the contributions of the current paper beyond those of [9], we provide a justification for the need to evaluate the performance of SSMA systems with random sequences.

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The authors are with the Department of Electrical Engineering and Systems Research Center, University of Maryland, College Park, MD 20742.

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Knowledge of the performance of DS/SSMA systems employing random signature sequences is desirable for several reasons. First, random signature sequences are often used in an attempt to match certain characteristics of extremely complex signature sequences with a very long period. Second, random signature sequences models may serve as substitutes for deterministic models when the communications engineer is given little or no information about the structure of the signature sequences to be used in the system. Finally, in cases that the number of active users is very large, the required computational effort for evaluation of the conditional error probability—given the number of interfering users—may become prohibitive when different deterministic signature sequences are used by the different users. In that case, the use of random signature sequences in the analysis remains the only hope for obtaining computable closed-form expressions. Networks with large finite (or even infinite in the limit) populations employing random access schemes coupled with DS/SS signaling and hybrid direct-sequence frequency-hopped (DS–FH) SSMA systems belong to this class of problems.

In the present paper, we evaluate the average probability of error at the output of the correlation receiver of both binary and quaternary synchronous and asynchronous DS/SSMA systems that employ random signature sequences and arbitrary time-limited chip waveforms, using an expanded form of the characteristic-function method introduced in [6] for deterministic signature sequences. This method, which is based on the integral of the characteristic function of multiple-access interference, provides an accurate approximation for most cases of interest and its accuracy can be improved (see [6]) by its combination with a series expansion method.

The contribution of this paper is three-fold.

1) The characteristic function of other-user interference in DS/SSMA systems with random sequences is derived; from that we derive the average error probability of the correlation receiver. Our derivation is different from that of [9] and, as such, is suitable for application to quaternary systems with and without offset and extension to coherent hybrid DS-FH SSMA systems (see [10]), as well as to broadcast DS and hybrid spread-spectrum systems (see [11]).
2) The validity of the random sequences model (which, as explained above, has many desirable features) is established by comparing the performance of DS/SSMA

Probability of Capture and Rejection of Primary Multiple-Access Interference in Spread-Spectrum Networks

Mohsen Soroushnejad, *Member, IEEE,* and Evaggelos Geraniotis, *Senior Member, IEEE*

***Abstract*— The probability of capture is evaluated for the situation in which several transmitters use the same spread-spectrum code for the attention of a single receiver. The first stage in the capture mechanism is that of the acquisition of capture. In the literature, randomization of the arrival time has been proposed to provide delay capture and the probability of this occurrence has been derived. We are concerned with the second stage, that of retaining capture in the presence of interference from contending users. The probability of retaining capture is computed via accurate approximations and upper bounds for direct-sequence, frequency-hopped, and hybrid spread-spectrum signaling formats and for different data modulation and demodulation schemes. The calculation of the overall probability of capture is carried out for spread-spectrum systems with and without forward-error-control; in the latter case, Reed-Solomon codes, as well as binary convolutional codes, are considered. Finally, the capability of rejecting primary multiple-access interference in spread-spectrum radio networks is examined by computing the maximum number of users that may contend for the same receiver, without causing the probability of capture to fall below some desirable level. It is observed that, in systems employing spread-spectrum signaling and forward-error-control coding, the capture performance follows a graceful degradation rather than a threshold behavior.**

I. Introduction

In networks employing spread-spectrum (SS) signaling and receiver-oriented transmission policies, the capture effect and the capability of rejecting primary multiple-access interference are important issues. However, except for the study of the acquisition of power capture considered in [1] and [2] and of delay capture considered in [3], no other quantitative results are available in the literature. This paper presents important quantitative results on the capture phenomena in SS packet radio networks.

Capture phenomena characterize the ability of a receiver to successfully receive a packet (with nonzero probability), even though part or all of the packet arriving at the receiver overlaps in time with other packets. The basic mechanism for capture is the ability of the receiver to synchronize with and lock on to one packet and subsequently reject other overlapping packets as noise (see [4]). We consider packet radio networks employing *receiver-oriented transmission policies.* When a node wishes to communicate with another node, it uses the SS code assigned to the intended receiver for its transmission. In this way, all neighbors of a receiving node may be competing for its attention and, since all are using the same SS code, collisions occur that may prohibit successful reception altogether. The multiple-access interference (MAI) generated during this mode of operation is termed *primary* MAI, in contrast to the more frequently encountered other-user interference generated when users with different SS codes are transmitting simultaneously, which is termed *secondary* MAI.

Besides SS radio networks with receiver-oriented transmission policies, our quantitative results for the probability of capture are also useful for *mobile satellite* (MSAT) SS radio networks. In some MSAT applications, different starting phases of the same signature sequence (SS code) are assigned to the various users. Although this is in principle a situation characterized by secondary interference, the average error probability of the typical user is equal to one minus the probability of retaining capture, a quantity evaluated in this paper.

Another motivation for our work stems from the need to find out if primary interference in SS packet radio networks causes a performance degradation that is *graceful* or follows *a threshold behavior.* The latter capture model was employed in the SS packet radio network of [5]. However, as we establish in this paper, capture probability degrades gracefully as the number of primary interferers increases; thus, the threshold model is not appropriate.

Here we focus on the problem of contention among many transmitters for a common receiver. It is assumed that all transmitted signals have the same received power at the receiver; therefore, the near-far problem is absent from our formulation. When the SS code employed does not repeat within a packet duration, the competing users' packets are strongly correlated over each data symbol, if they arrive at a receiver simultaneously, but pseudoorthogonal, if they arrive with a time offset. This property allows the first packet to be captured and successfully received, while the others are rejected as noise with some probability. In general, there is a vulnerable period at the beginning of a packet, denoted by T_a

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M. Soroushnejad was with the Department of Electrical Engineering and the Systems Research Center, University of Maryland, College Park, MD 20742. He is now with AT&T Bell Laboratories, Holmdel, NJ 07703.

E. Geraniotis is with the Department of Electrical Engineering and the Systems Research Center, University of Maryland, College Park, MD 20742.

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Multireception Probabilities for FH/SSMA Communications

Thomas J. Ketseoglou and Evaggelos Geraniotis, *Senior Member, IEEE*

***Abstract*—Exact expressions for the probabilities $P(l, m-l|k)$ of l correct packet receptions and $m-l$ erroneous ones, out of total k packets contending in a slot, are presented for the case of frequency-hopped spread-spectrum random-access slotted networks employing random frequency hopping patterns. These expressions are difficult to evaluate numerically for values of $m > 3$. However, our numerical analysis indicates that under light traffic conditions these probability values are very close to the ones provided by the independent receiver operation assumption, under which the distribution of multireception obeys the binomial law.**

I. Introduction and Problem Formulation

An important quantity in spread-spectrum radio networks is the probability that exactly l out of m packet transmissions are successful, given that k users attempt to transmit their packets simultaneously; this quantity is denoted by $P(l, m-l|k)$. The integer m denotes the number of receivers of interest; in most practical situations, $m \leq k$. Specifically, in problems involving multireception with a bank of m receivers at a single location, the probability mass function

$$P(l, m-l|k) \quad \text{for } l = 0, 1, \cdots, m \quad \text{and} \quad m \leq k$$

describes the multireceiver performance. Moreover, in problems in which the evaluation of the throughput or delay of various network protocols is desirable (e.g., [1], [2]),

$$\begin{aligned} P_c(l|k) &= P_l(l, k-l|k) \\ &= \binom{k}{l} P(l, k-l|k) \quad \text{for } l = 0, 1, \cdots, k \end{aligned}$$

is required where $P_c(l|k)$ denotes the probability of any l correct packet receptions out of k simultaneous transmissions.

Consequently, in practical spread-spectrum packet radio networks, there is an undisputed need to evaluate the probabilities $P(l, m-l|k)$ and $P_l(l, m-l|k) = \binom{m}{l} P(l, m-l|k)$ ($l = 0, 1, \cdots, m$ and $m \leq k$) for different spreading signaling formats, data modulation schemes, and error-control coding schemes.

In this paper we evaluate these quantities for frequency-hopped (FH) spread-spectrum multiple-access (SSMA) networks. Specifically, we develop exact expressions for $P(l, m-l|k)$ for FH/SSMA systems with RS encoding and various types of minimum-distance decoding. These exact expressions are valid for all values of l, m, and k but are difficult to compute numerically, since their computational complexity grows exponentially with m. Numerical results obtained from these exact expressions are compared with those obtained via the independence receiver operation assumption (IROA) method commonly used in the literature [1], [2]. This method assumes that packet errors among different receivers are mutually independent, which greatly simplifies the computation. It is established that, for $m = 2$ and $m = 3$, the independence assumption is valid for a wide range of values of the ratio k/q. It is also shown that it is valid for all m under light traffic $k/q \ll 1$. Although we conjecture that the approximation based on the independence assumption is satisfactory for all $m \geq 4$ and any value of k/q, additional work is required to prove this claim.

Derivations and comparisons are carried out for FH/SS systems employing MFSK modulation with noncoherent demodulation and Reed–Solomon (RS) (n, k_c) forward error-control coding with erasures-only, errors-only, and errors/erasures minimum-distance [3] decoding. It is assumed that each RS symbol carries one M-ary symbol (i.e., $n = M$), that each FH dwell time (hop) carries one RS symbol, and that one RS codeword per packet is transmitted. The frequency-hopping patterns of the different users are modeled as random memoryless hopping patterns [4]. Thus, each of q available frequencies is visited with equal probability and independently of each other during any dwell time (hop) by each user and mutually independent hopping patterns are assigned to distinct users. The various users are packet-synchronous but may be hop-asynchronous; in this context, both hop-synchronous and hop-asynchronous FH/SSMA systems are considered. Also thermal noise modeled as additive white Gaussian noise (AWGN) is incorporated to the analysis.

This paper is organized as follows. In Section II exact expressions for $P(l, m-l|k)$ are derived for all cases of interest enumerated above. In Section III, the approximate expressions based on the independence assumption are cited. Numerical results and comparisons of the two approaches are presented provided in Section IV. In Section V, conclusions are drawn.

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T. J. Ketseoglou was with the Department of Electrical Engineering, University of Maryland, College Park, MD 20742. He is now with Siemens, Athens, Greece.

E. Geraniotis is with the Department of Electrical Engineering and the Systems Research Center, University of Maryland, College Park, MD 20742.

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Performance Comparison of Different Spread-Spectrum Signaling Schemes for Cellular Mobile Radio Networks

Mohsen Soroushnejad, *Member, IEEE*, and Evaggelos Geraniotis, *Senior Member, IEEE*

***Abstract*—A comparison of different spread-spectrum signaling schemes in a cellular mobile radio network in terms of throughput and packet error probability is conducted. Bounds on the bit and packet error probabilities are derived for data modulation schemes with binary phase shift keying with coherent demodulation and *M*-ary frequency-shift keying with noncoherent demodulation. Reed-Solomon coding is employed for error-correction purposes. In all cases, the effect of varying interference power (according to some inverse power of distance) of the desired signal, of the interfering signals, and of Rayleigh nonselective channel fading is accurately taken into account.**

The throughput in the mobile-to-base transmission mode is evaluated for the above data modulation, demodulation, and forward-error-control coding schemes. Our comparison shows that, under the varying interference power model, the frequency-hopped scheme performs best among all schemes with the same bandwidth. Power control mechanisms are required to improve the performance of direct-sequence systems. It has further been observed that coding significantly enhances the performance of the above schemes.

I. Introduction

In mobile cellular radio networks employing spread-spectrum (SS) signaling, the effect of the varying received power levels due to interfering signals is a major issue determining system performance. Although the literature on spread-spectrum multiple-access (SSMA) systems (see references) provides the average error probability of frequency-hopped (FH), direct-sequence (DS), and hybrid (FH–DS) SSMA systems under a variety of operating scenarios, no accurate evaluation of the effects of varying power interfering signals is currently available. A comparison of the performance of the various SS signaling formats in this context has not been undertaken either. Moreover, although DS systems are known to suffer more from the near–far problem than FH systems, no accurate quantification of this difference is available for cellular networks. Our paper is motivated by these two issues.

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M. Soroushnejad was with the Department of Electrical Engineering and Systems Research Center University of Maryland College Park, MD 20742. He is now with the AT&T Bell Laboratories, Holmdel NJ 07703.

E. Geraniotis is with the Department of Electrical Engineering and Systems Research Center University of Maryland College Park, MD 20742.

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Before elaborating upon the contributions of this paper, we review the most relevant previous work in the area of mobile SS radio networks. In the cellular radio network of [1], which employs FH signaling, the model of the SSMA interference was not sufficiently accurate, although the effects of varying other-user interference power and channel fading have been taken into account properly. By contrast, the models of [2] take into consideration the FH/SS modulation in an accurate way, but leave out the effects of varying received power and fading on other-user interference. This is due to an upper bound on the conditional probability of error, given that one or more hits have occurred (see [3]), which is independent of the received power of other-user interference. In our own work of [4], we combine the models of [1] and [2] and provide a detailed analysis of the effects of FH/SS modulation and error control coding, as well as of varying received power and fading on other-user interference. However, the presentation of [4] was limited to cellular networks employing FH/SS signaling and did not provide a comparison of the performance of different SS signaling schemes.

In this paper, we complement and enhance the results of [1], [2], and [4] by providing a precise characterization of multiuser interference for DS and hybrid FH-DS signaling in cellular mobile radio networks, and compare the performance of these schemes in terms of throughput and packet error probability. The results presented in our paper differ from the ones given in [1] in two ways. First, we base our results on a communication system approach, while in [1] the MA protocols are analyzed in an information theoretic manner. Second, the comparison in [1] is between the traditional frequency-division multiple-access (FDMA) protocol and the slow frequency-hopped (SFH) system, while the comparison in our paper is among different code-division multiplexing schemes. This paper also extends our previous work of [4] in three directions. First, for cellular networks employing FH/SS, an accurate analysis of the bit error probability of noncoherent BFSK demodulation is performed based on the recent results of [11]; this completes and validates the results of [4]. Second, cellular networks employing DS/SS and hybrid FH–DS/SS modulation schemes are analyzed in detail. Third, the performance of all three FH, DS, and hybrid SS signaling schemes is compared for a cellular network environment under a common bandwidth allocation.

In a cellular radio network employing DS or hybrid signaling and forward-error control (FEC) coding, the bit and

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MULTI-ACCESS STRATEGIES FOR AN INTEGRATED VOICE/DATA CDMA PACKET RADIO NETWORK

Mohsen Soroushnejad and Evaggelos Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD 20742

ABSTRACT

The problem of voice/data integration in a random-access radio network employing the ALOHA protocol in conjunction with retransmission control is investigated. Code-division multiple-access (CDMA) is used as a suitable modulation in a radio environment to decrease the effect of multiple-access interference. Multi-access control strategies are introduced which take advantage of the multiple-access capability of the CDMA channel to accommodate several voice calls simultaneously, while the data users contend for the remaining (if any) multiple-access capability of that channel. The retransmission probabilities of the backlogged data users are updated based on estimates of data backlog and number of established voice calls, which are obtained from the side information about the state of channel activities. A two-dimensional Markovian model is developed for the voice and data traffic, with the data backlog and number of established voice calls representing the state of the system. Based on this model, the voice-call blocking probability, the throughput of both traffic types, and the delay of the data packets are evaluated and the tradeoffs between the parameters of different traffic types are quantified. It is observed that by taking advantage of multiple-access capability of the CDMA channel in the control of data traffic, we may achieve movable-boundary channel access in the code domain.

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PERFORMANCE OF CELLULAR FREQUENCY-HOPPED SPREAD-SPECTRUM RADIO NETWORKS

Jeffrey W. Gluck and Evaggelos Geraniotis

Abstract

We characterize multiple-access interference for cellular mobile networks, in which users are assumed to be Poisson-distributed in the plane and employ frequency-hopped spread-spectrum signaling with a transmitter-oriented assignment of frequency-hopping patterns. Exact expressions for the bit error probabilities are derived for binary coherently demodulated systems without coding. Approximations for the packet error probability are derived for coherent and noncoherent systems and these approximations are applied when forward-error-control coding is employed. In all cases, the effects of varying interference power are accurately taken into account according to some propagation law.

Numerical results are given in terms of bit error probability for the exact case and throughput for the approximate analyses. Comparisons are made with previously derived bounds and it is shown that these tend to be very pessimistic.

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ANALYSIS OF COHERENT RANDOM-CARRIER CODE-DIVISION MULTIPLE-ACCESS FOR HIGH-CAPACITY OPTICAL NETWORKS

B. Ghaffari and E. Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD. 20742

ABSTRACT

In this paper we provide an accurate analysis of the performance of a random-carrier (RC) code-division multiple-access (CDMA) scheme recently introduced for use in high-capacity optical networks. According to this scheme coherent optical techniques are employed to exploit the huge bandwidth of single-mode optical fibers and are coupled with spread-spectrum direct-sequence modulation in order to mitigate the interference from other signals due to the frequency overlap caused by the instability of the carrier frequency of the laser, or to the mistakes in the frequency coordination and assignment.

The average bit error probability of this multiple-access scheme is evaluated by using the characteristic function of the other-user interference at the output of the matched optical filter. Both phase noise and thermal noise are taken into account in the computation. Time-synchronous as well as asynchronous systems are analyzed in this context. Binary phase-shift-keying (BPSK) and on-off-keying (OOK) data modulation schemes are considered. The analysis is valid for arbitrary values of the spreading gain and the number of interfering users. The performance evaluation of RC CDMA establishes the potential advantage in employing hybrids of wavelength-division multiple-access (WDMA) and CDMA to combat inter-carrier interference in dense WDMA systems.

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COMPARISON OF WDMA AND HYBRID WDMA/CDMA FOR THE MULTIPLEXING OF OPTICAL SIGNALS

B. Ghaffari and E. Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD. 20742

ABSTRACT

In this paper, we first provide an accurate analysis of the performance of coherent dense wavelength-division multiple-access (WDMA) schemes introduced for use in high-capacity optical networks. In this analysis, the effects of interference from other signals due to the frequency overlap caused by the instability of the carrier frequency of the laser, or to mistakes in the frequency coordination and assignment, are taken into account. Phase noise and thermal noise are also taken into consideration. Dense WDMA is then coupled with spread-spectrum direct-sequence modulation in order to mitigate the effect of the interference from other signals. The performance of this hybrid of WDMA and code-division multiple-access (CDMA) scheme is also analyzed and compared to that of pure WDMA.

The average bit error probability of the dense WDMA and WDMA/CDMA schemes is evaluated by integrating the characteristic function of other-user interference at the output of the matched optical filter. Time-synchronous, as well as asynchronous systems, are analyzed in this context. Binary phase-shift-keying (BPSK) and on-off-keying (OOK) data modulation schemes are considered. The numerical results provided in this paper quantify accurately for first time the multiple-access capability of dense WDMA schemes and the advantages offered by employing hybrids of WDMA and CDMA.

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Robust Data Fusion for Multisensor Detection Systems

EVAGGELOS GERANIOTIS, SENIOR MEMBER, IEEE, AND YAWGENG A. CHAU, STUDENT MEMBER

Abstract—Minimax robust data fusion schemes for multisensor detection systems with discrete-time observations characterized by statistical uncertainty are developed and analyzed. The observations are assumed to be i.i.d and the decisions of all sensors independent, when conditioned on either of the two hypotheses. The probability distributions of the sensor observations are only known to belong to uncertainty classes determined by 2-alternating Choquet capacities. Block, sequential, and serial fusion rules are considered. The performance measures employed and made robust with respect to the uncertainties include the error probabilities of the hypothesis testing problem in the block fusion case and the error probabilities and expected numbers of samples or sensors in the sequential and serial fusion cases. For different sensor observation statistics, the minimax robust fusion rules are derived for two asymptotic cases of interest: a) when the number of sensors is large and b) when the number of times the fusion center collects the local (sensor) decisions is large. Moreover, for the case of identical sensor observation statistics and a large number of sensors, it is shown that there is no loss in optimality, if local tests using likelihood ratios and equal thresholds are employed in the sequential fusion rule. In all situations, the robust decision rules at the sensors and the fusion center are shown to make use of likelihood ratios and thresholds that depend on the least-favorable probability distributions of the uncertainty class describing the statistics of sensor observations.

I. INTRODUCTION

DISTRIBUTED DETECTION and data fusion systems have recently attracted considerable attention (see [1]–[7], and [20]), as they are used in many problems of practical interest. In [1] it was shown that the optimal scheme of distributed detection with a fixed fusion rule involves using likelihood ratio tests at the sensors for local decisions with dependent thresholds that satisfy coupled equations. In [3] the thresholds of the local decisions were held fixed and the fusion rule was optimized. In [5] and [6] the combined problem of optimizing both the fusion rule and the local decisions was addressed. Sequential decisionmaking was considered in [2], [4], and [20]. In [2] the cost consisting of the Bayesisan risk and the expected sample size was optimized, and each sensor (not the fusion center) decides whether to stop or make a decision. In [4] it was established that, when a fusion center was employed to make the final decision and the number of sensors large, equal thresholds can be used without any loss of optimality for the block fusion rule; not similar result for the sequential fusion rule was derived. It was proved in a recent paper [20], that for the fusion rule of fixed sequential decisionmaking, the local sensor decisions were optimized by employing likelihood ratio tests on their individual thresholds. In [7] a serial fusion rule that combined the decisions of previous sensors with the current observation from the last sensor was considered.

In all this previous work, the statistics of the observations were assumed to be completely known *a priori*, an assumption not always satisfied in realistic situations in which only partial or incomplete knowledge of the statistics may be available. In our own work of [8] we addressed the problem of minimax robust distributed detection without a fusion center for general uncertainty classes characterized by 2-alternating Choquet capacities. There the two sensors coordinated their decisions to jointly optimize a common cost function, and that was done so as to guarantee a minimum level of acceptable performance within the uncertainty class.

In this paper, we consider several problems of data fusion from sensors with observations experiencing statistical uncertainty and design robust fusion rules and local decision schemes for the sensors, which guarantee acceptable performance levels despite the uncertainty. The design philosophy is that of *minimax robustness*, meaning that we derive the best combination of local-decisions and fusion-rule for the least-favorable (worst-case) situation presented by the statistics of the observations in the assumed classes; if this robust scheme guarantees a desired level of performance under worst-case conditions, then for all other situations in the uncertainty class its performance will be better.

This paper makes two primary contributions. The first is the individual robustification of the three fusion rules, (block, sequential, and serial described next) to the uncertainties in the sensor observations described in the previous paragraph, which constitutes a desirable extension of the well-known theory of minimax robustness from single-detector systems to multisensor detection systems (see [9]–[14]). The second is the evaluation of the performance of the three fusion schemes for the cases of a) a

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The authors are with the Department of Electrical Engineering, University of Maryland, College Park, MD 20742.

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Distributed Multisensor Parameter Estimation in Dependent Noise

Yawgeng A. Chau and Evaggelos Geraniotis, *Senior Member, IEEE*

***Abstract*— The problem of distributed estimation of a weak nonrandom location parameter θ in additive stationary dependent noise is addressed. We consider multisensor configurations with and without a coordinator. Dependence in the sensor observations is described by m-dependent, ϕ-mixing and ρ-mixing models. Two cases of interest are addressed: i) the one in which sensor observations are dependent across time but independent across sensors and ii) the one in which sensor observations are dependent across both time and sensors. Because high-order statistics of dependent observations are generally difficult to characterize, maximum-likelihood estimates may be impossible to derive or to implement. Instead, suboptimal M-estimates $\hat{\theta}_N^{(k)} (k = 1, 2, \cdots, K)$ are employed by the K sensors, which solve $\sum_{i=1}^N g_k\left(X_i^{(k)} - \hat{\theta}_N^{(k)}\right) = 0$ where $X_i^{(k)} (i = 1, 2, \cdots, N)$ and $g_k(\cdot)$, respectively, denote the sensor observations and memoryless nonlinearities.**

The sensor nonlinearities g_k are chosen so as to minimize the appropriate cost functions. In the absence of a coordinator, the common cost function consists of the sum of the mean square errors (MSEs) of the individual sensor M-estimates $\hat{\theta}_N^{(k)}$ and the mean square of their pairwise differences. In the presence of a coordinator, the cost function is the MSE of its estimator $\hat{\theta}_N$ formed as the maximum-likelihood estimate of θ based on the individual sensor M-estimates. Minimizing the above cost functions yields the optimal sensor nonlinearities g_k as solutions of linear integral equations. Numerical examples for stationary m-dependent Cauchy noise are provided in support of our analysis; they provide a comparison of the various estimation schemes and establish that our schemes outperform the ones that ignore dependence in sensor observations.

I. Introduction

DISTRIBUTED estimation has attracted considerable attention in recent years (see [1]–[4]). However, neither the dependence in the observation sequence of each individual sensor, nor the cross-dependence in the observation sequences of different sensors have been taken into consideration in previous work. In many practical situations, where the sampling rate is high or the distributed estimators (sensors) are relatively close to each other geographically, the sensor observations are individually dependent and also dependent across sensors. Suitable consideration and incorporation of this dependence in the distributed estimation algorithms is expected to provide considerable gains in the performance over the schemes that ignore the dependence.

In this paper, we address two problems of distributed estimation of a location parameter in dependent noise across time and/or sensors: i) distributed estimation without a coordinator (fusion center) and ii) distributed estimation with a coordinator.

Before describing the two distributed estimation schemes, we discuss the model for the sensor observations. The dependent sensor observation sequences are assumed to be stationary and are modeled as m-dependent, ϕ-mixing, or ρ-mixing sequences. The tutorials [5] and [6] provide detailed descriptions of these models and of the associated center limit theorems.

It is well known that, in centralized (single sensor) estimation problems, the estimate of a location parameter is obtained by optimizing a particular nonlinear function (likelihood function or mean square error) of the observations. However, when there is dependence in the observations of the type discussed in the previous paragraph, maximum-likelihood (ML) estimators are typically impossible to derive or too complex to implement. Therefore, in our problem, which is characterized by strong dependence in the individual sensor observations or across sensors, we use the class of estimators introduced by Huber in [7]; however, the selection of the nonlinearities involved in these estimators is performed on the basis of multi-sensor coordination.

The estimators of [7], termed M-estimators, involve additive functionals of nonlinear functions $\varphi_k(\cdot)$ [for $k = 1, 2, \cdots, K$] with derivatives $g_k(\cdot)$. The sensor estimate $\hat{\theta}_N^{(k)}$ is obtained by solving the equation

$$\sum_{i=1}^{N} g_k\left(X_i^{(k)} - \hat{\theta}_N^{(k)}\right) = 0$$

where $X_i^{(k)}$ denotes the ith observation $(i = 1, 2, \cdots, N)$ collected by the kth sensor from a group of K sensors. Of interest here is the asymptotic case of a large common sample size N, since the location parameter $\theta > 0$ is assumed to be very small in amplitude, which makes large sample sizes necessary in order to guarantee acceptable performance.

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Y. A. Chau was with the Department of Electrical Engineering and Systems Research Center, University of Maryland, College Park, MD 20742. He is now with the Department of Electrical Engineering, Yuan-Ze Institute of Technology, Taiwan, R.O.C.

E. Geraniotis is with the Department of Electrical Engineering and Systems Research Center, University of Maryland, College Park, MD 20742.

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ROBUST DISTRIBUTED DISCRETE-TIME BLOCK AND SEQUENTIAL DETECTION IN UNCERTAIN ENVIRONMENTS

Evaggelos Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD 20742

ABSTRACT

Two detectors making independent observations must decide which one of two hypotheses is true. Both fixed-sample-size (block) detection and sequential detection are considered. The decisions are coupled through a common cost function which for tests with fixed sample size consists of the sum of the error probabilities while for sequential tests it comprises the sum of the error probabilities and the expected sample sizes. The probability measures which govern the statistics of the i.i.d. observations belong to uncertainty classes determined by 2-alternating capacities.

A minimax robust (worst-case) design is pursued according to which the two detectors employ fixed-sample-size tests or sequential probability ratio tests whose likelihood ratios and thresholds depend on the least-favorable probability measures over the uncertainty class. For the aforementioned cost function the optimal thresholds of the two detectors turn out to be coupled. It is shown that, despite the uncertainty, the two detectors are thus guaranteed a minimum level of acceptable performance.

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DISTRIBUTED DETECTION FROM MULTIPLE SENSORS WITH CORRELATED OBSERVATIONS

Yawgeng A. Chau and Evaggelos Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD 20742

ABSTRACT

We address two problems of distributed multi-sensor detection without a fusion center with dependent observations across time and sensors. In the first problem, the observation sequence of each sensor consists of a common weak signal in additive stationary dependent noise; the objective of the sensors is to cooperatively detect the presence of the weak signal. In the second problem, the observation sequences of each sensor under the two hypotheses are arbitrary stationary dependent sequences; the objective of the sensors is to cooperatively disrciminate between the two hypotheses. The dependence in the observations across time and sensors is modeled by m-dependent, ϕ-mixing, or ρ-mixing processes.

For both the weak-signal detection and the discrimination problem the performance of the two-sensor configuration is measured by an average cost, which couples the decisions of the sensors. The analysis and design are based on a common large sample size. The design criteria for the test satistics of the sensors, which constist of sums of memoryless nonlinearities, are established by using an approximation to the asymptotic rate (obtained via the large deviations principle) of the error probabilities involved in the average cost. The optimal nonlinearities are obtained as the solutions of linear coupled or uncoupled integral equations involving the univariate and bivariate probability densities of the sensor observations. Numerical results based on simulation are provided for specific cases of practical interest; they establish that the performance of the proposed schemes is superior to the one which ignores the dependence across time and/or sensors, for each one of the two detection problems.

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QUANTIZATION AND FUSION IN MULTI-SENSOR SYSTEMS FOR THE DETECTION OF WEAK SIGNALS

Yawgeng A. Chau and Evaggelos Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD 20742

ABSTRACT

A class of problems involving quantization and data fusion in multi-sensor detection systems is addressed. The observation sequence of each sensor consists of a common weak signal in additive stationary dependent noise; the objective of the fusion center is to detect the presence of the weak signal. We consider two cases: in the first, the samples of the noise sequence of each sensor are dependent but the noise sequences of different sensors are mutually independent; in the second, the noise sequences are dependent across time and sensors. The dependence in the sensor noise samples is modeled by m-dependent, ϕ-mixing, or ρ-mixing processes. The fusion schemes considered are: (i) forming test statistics at the sensors by passing the observations through memoryless nonlinearities, summing them up, and then combining linearly the sensor test statistics at the fusion center without previous quantization; (ii) quantizing (memorylessly) each sensor observation and then applying again a linear fusion rule (LFR).

To guarantee high-quality performance, a common large sample size is employed by each sensor and an asymptotic analysis is pursued. By maximizing the Asymptotic Relative Efficiency (ARE) of the fusion center, design criteria (consisting of extensions of the efficacy functional to the multi-sensor case) are developed for deriving the optimal sensor nonlinearities and quantizers used in the LFR. These nonlinearities are obtained as the solutions of linear coupled or uncoupled integral equations involving the univariate and bivariate probability densities of the sensor observations. Numerical results based on simulation are presented for the detection of a weak signal in additive dependent Caucy noise; the relative performance of the quantization/fusion schemes described above is compared and their superiority to schemes that ignore dependence across time and/or sensors in sensor observations is established.

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MULTI-SENSOR CORRELATION AND QUANTIZATION IN DISTRIBUTED DETECTION SYSTEMS

Yawgeng A. Chau and Evaggelos Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD 20742

ABSTRACT

Problems of multi-sensor correlation and quantization in distributed systems with a fusion center used for the detection of weak signals in m-dependent or mixing stationary noise are addressed. Two models are considered for the correlation in the sensor observations: (a) the samples of the noise sequence of each sensor are dependent but the noise sequences of different sensors are mutually independent; and (b) the noise sequences are dependent across time and sensors. The fusion schemes introduced and analyzed are: (i) forming test statistics at the sensors by passing the observations through memoryless nonlinearities, summing them up, comparing to a threshold and then trasmitting the binary decision to the fusion center which makes the final decision according to a majority rule; (ii) forming the sensor test statistics as in (i) and quantize them to a number of levels before transmitting the non-binary information to the fusion center where the information from the various sensors is combined linearly and compared to a threshold

To achieve high-quality performance, a common large sample size is employed by each sensor and an asymptotic analysis is pursued. Approximations to the asymptotic rate of the error probability of the fusion center [for fusion scheme (i)] and to the deflection criterion [for fusion scheme (ii)] are derived and from them suitable performance measures are developed, whose maximization yields the optimal sensor nonlinearities and quantizers for the above fusion rules. These nonlinearities are obtained as the solutions of linear coupled or uncoupled integral equations involving the univariate and bivariate probability densities of the sensor observations. The performance of the quantization/fusion schemes described above is compared via simulation for the detection of a weak signal in additive ρ-mixing Caucy noise. The superiority of the fusion rules introduced in this paper to schemes that ignore dependence across time and/or sensors in sensor observations is established.

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QUANTIZATION AND FUSION FOR MULTI-SENSOR DISCRIMINATION FROM DEPENDENT OBSERVATIONS

Yawgeng A. Chau and Evaggelos Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD 20742

ABSTRACT

Schemes for quantization and fusion in multi-sensor systems used for discriminating between two sequences of dependent observations are introduced and analyzed. The observation sequences of each sensor under the two hypotheses are arbitrary stationary dependent sequences that can not be modeled as signal in additive noise; the objective of the fusion center is to disrciminate between the two hypotheses. These observation models are well motivated by practical multi-sensor target discrimination problems. Two cases are considered: in the first, the observation sequences of the sensors are individually dependent but jointly mutually independent; in the second case, the observation sequences are dependent across both time and sensors. The dependence in the observations across time and/or sensors is modeled by m-dependent, ϕ-mixing, or ρ-mixing processes. The following four quantization/fusion schemes are considered: (a) forming test statistics at the sensors by passing the observations through memoryless nonlinearities, summing them up, and fusing these test statistics without previous quantization; (b) quantizing uniformally (with equidistant breakpoints) each sensor observation and then fusing; (c) quantizing optimally each sensor observation and then fusing; and (d) using the sensor test statistic of (a) to make binary decisions and then fusing the binary decisions. To guarantee high-quality performance, a common large sample size is employed by each sensor and an asymptotic analysis is pursued. Design criteria are developed from the Bayesian cost of the fusion center for deriving the optimal memoryless nonlinearities of the sensor test statistics and the sensor quantizer parameters (quantization levels and breakpoints). These design criteria are shown to involve an extension of the generalized signal-to-noise ratio used in single-sensor detection and quantization. The optimal nonlinearities and quantizers are obtained as the solutions of linear coupled or uncoupled integral equations involving the univariate and bivariate probability densities of the sensor observations. Numerical results based on simulation are presented for specific cases of practical interest to compare the relative performance of the four quantization/fusion schemes described above and to establish their superiority to schemes that ignore the dependence across time and/or sensors in the observations.

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work; for example, we did not treat the high robustness to channel errors, which is one of the typical properties of most versions of the stack algorithm [3].

There are several versions of the stack algorithms that can be implemented (and slightly modified) for our purpose. For example, the stack algorithm with Q-ary, instead of binary, splitting [5] can be analyzed easily with exactly the same techniques. We know that $Q=3$ optimizes the throughput when the packets are one slot long. However, this property does not persist when the length of packet increases. For example, when all packets are of length M we can show by expansion of the marginal maximum throughput (see [13] for details) that

$$Q=3 \Rightarrow \mu_{\max} \approx 0.4114 + O(M^{-1})$$

$$Q=4 \Rightarrow \mu_{\max} \approx 0.3785 + O(M^{-1}).$$

Thus, the binary stack algorithm outperforms the other generalized Q-ary versions. It is also possible to improve the tree algorithms by an adjustment that "saves doomed slots," [3]. The throughput is a few percent higher, but the robustness to channel errors slightly decreases (risk of deadlocks).

In conclusion, we see that the basic binary stack algorithm analyzed in this correspondence exhibits desirable properties such as simplicity, robustness, and stability. It offers a strong challenge to the deficient but widely employed binary exponential back off protocol for local area network communication.

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Robust Matched Filters for Noise Uncertainty Within Two Alternating Capacity Classes

EVAGGELOS GERANIOTIS, SENIOR MEMBER, IEEE

Abstract—The problem of designing matched filters that are robust against uncertainty in the statistics of a noise process, modeled by two alternating Choquet capacities is addressed. The robust design is based on the maximin signal-to-noise ratio. The problem is formulated and solved for both discrete-time and continous-time matched filters with uncertainty in either the autocorrelation function or the spectral measure of the noise. Explicit solutions are obtained that are characterized by the Huber–Strassen derivative of the capacity generating the class with respect to a Lebesgue-like measure on a suitable interval.

I. Introduction

Robust signal processing techniques have received considerable attention in the last 15 years (see the tutorial in [1]). In particular, robust matched filtering problems have been formulated and partially solved in [2] for continuous-time and in [3] for discrete-time observations. In such problems there is uncertainty in the statistics of either the signal, or the noise, or both. Several uncertainty models for the signal and the noise were considered in [2] and [3].

We shall focus on uncertainty in the noise autocorrelation function (time domain) or the noise spectral measure (frequency domain) and study uncertainty classes determined by two alternating Choquet capacities [4]–[6], which were not examined in [2], [3]. Both discrete-time and continuous-time formulations of the robust matched filtering problem with noise uncertainty within capacity classes are considered. The two alternating Choquet capacities classes include several useful uncertainty models like the ϵ-contaminated class [4], the total variation class [4], the band class [5] and the p-point class [6], each of which has been popular among statisticians.

The robust matched filtering problem for noise uncertainty involves the identification of a worst case noise statistic over the allowable uncertainty class and the derivation of a filter matched to this worst case noise. When this robust filter is used, the signal-to-noise ratio is guaranteed to be better for any noise statistic in the uncertainty class other than the worst-case statistic.

This correspondence is organized as follows. In Section II the notation, the basic concepts, and some general results for uncertainty classes generated by two alternating capacities are cited. In Section III four problems of robust matched filtering with noise uncertainty are formulated. In Section IV a complete characterization of maximin robust matched filters for the aforementioned four problems is provided.

II. Uncertainty Classes Generated by Choquet Capacities

Suppose that Ω is a compact set and F is the σ-algebra generated by its subsets. We assume that the measures m are only known to lie in a convex class generated by a Choquet two

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The author is with the Electrical Engineering Department and Systems Research Center, University of Maryland, College Park, MD 20752.

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Optimal and Robust Memoryless Discrimination from Dependent Observations

Douglas Sauder and Evaggelos Geraniotis, *Senior Member, IEEE*

Abstract—Discrimination is considered between two possible sources based on dependent observations of their output. The discrimination problem is modeled by means of a general binary hypothesis test, the main emphasis being on situations that cannot be modeled as signals in additive noise. The observations are modeled as stationary m-dependent or ρ-mixing processes. The structure of the discriminator is such that the observations are passed through a memoryless nonlinearity and summed up to form a test statistic, which is then compared to a threshold. Only fixed sample size tests are considered. Four different performance measures, which resemble the signal-to-noise ratios encountered in the signal in additive noise problems, are derived under different problem formulations. The optimal nonlinearities for each of the performance measures are derived as solutions to various integral equations. For three of the four performance measures we have successfully obtained robust nonlinearities for uncertainty in the marginal and the joint probability density functions of the observations. Computer simulation results that demonstrate the advantage of using our nonlinearities over the i.i.d. nonlinearity under the probability of error criterion are presented.

Index Terms—Discrimination, robustness, memoryless nonlinearity, ρ-mixing.

I. Introduction

THE TERM "discrimination" is used in this paper to refer to a detection problem in which the "noise" characteristics under the two hypotheses are substantially different. This is in contrast to the case of an additive noise channel, where it is assumed that an independent noise process is added to the signal as it traverses the channel. In our model, we assume that all randomness is in the signal itself, and that transmission through the channel is noiseless. This model is especially appropriate in radar problems sometimes referred to as target discrimination or target identification. In such problems, the output of the signal processing device must indicate which of several targets is present. This discrimination or identification is to be performed after an initial decision that some object is present. Thus, under each possible hypothesis, one observes the random output of a particular source and must decide which particular source is present. For the purposes of our paper, we shall state the problem as a binary hypothesis testing problem:

$$H_0: \{X_k\} \text{ has the distribution } F_0$$
$$H_1: \{X_k\} \text{ has the distribution } F_1. \qquad (1.1)$$

Throughout this paper, as in (1.1), we use the symbol F_i to denote the distribution of the entire process under H_i, which in general is not independent and identically distributed (i.i.d.). We denote by f_i and $f_i^{(n)}$ and the marginal and nth-order joint densities respectively, of the process with respect to the measure ν under H_i. The observation process $\{X_k\}$ is assumed to be stationary and ρ-mixing (which implies ergodicity). We will be concerned with the asymptotic performance of various discriminators, but we assume that the process distributions remain fixed, which is in contrast to the ARE performance criterion where the "distance" between the two distributions converges to zero as the sample size increases.

Most of the literature in this area has focused on situations that can be modeled as a signal in additive noise. Poor and Thomas [1] and Halverson and Wise [2] address the problem of memoryless detection for m-dependent and ϕ-mixing noise, respectively, under the ARE performance measure. Sadowsky and Bucklew [3] also address the problem of signal detection in ϕ-mixing noise, but from a nonlocal standpoint. They derive a nonlocal performance measure which we also derive here as S_2. Poor [6] obtains results in memoryless discrimination, but only for the locally optimum case under the ARE performance measure. Related results in robustness have also focused primarily on the signal in additive noise model. Poor [8] obtains the robust detector for a model of additive moving average noise. Moustakides and Thomas in [11] obtain the robust detector for a model in which the multivariate distribution of the additive noise belongs to an ϵ-contaminated uncertainty class, while in [22] they obtain the robust detector under the ARE performance measure for a weak signal in additive ϕ-mixing noise with uncertainty in the univariate and bivariate pdfs. Poor [16] considers the problem of minimax robustness under a nonlocal performance measure for i.i.d. observations.

The goal of this paper is to present a thorough discussion of the use of memoryless fixed sample size methods to discriminate between two sources that produce correlated outputs. These memoryless discriminators are characterized by their use of a test statistic of the form

$$T_n(x) = \sum_{i=1}^{n} g(x_i) \qquad (1.2)$$

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The authors are with the Department of Electrical Engineering and Systems Research Center, University of Maryland, College Park, MD 20742.

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ONE-STEP MEMORY NONLINEARITIES FOR SIGNAL DETECTION AND DISCRIMINATION FROM CORRELATED OBSERVATIONS

D. Sauder and E. Geraniotis

ABSTRACT

New detectors based on one-step memory nonlinearities and employing the test statistic $\sum_{j=0}^{n-1} g(X_j, X_{j+1})$ are introduced. Problems of discrimination between two arbitrary stationary m-dependent or mixing sequences of observations and problems of detecting a weak signal in additive stationary m-dependent or mixing noise are considered in this context. For each problem, the nonlinearity g is optimized for performance criteria, such as the generalized signal-to-noise ratio and the efficacy and is obtained as the solution to an appropriate linear integral equation. Moreover, the schemes considered can be robustified to statistical uncertainties determined by 2-alternating capacity classes, for the second-order joint pdfs of the observations, and by bounds on the correlation coefficients of time-shifts of the observation sequence, for the third- and fourth-order joint pdfs. Evaluation of the performance of the new schemes via simulation reveals significant gains over that of detectors employing memoryless nonlinearities or the i.i.d. nonlinearity.

D. Sauder is with Locus, Inc., Alexandria, VA, and the Department of Electrical Engineering, University of Maryland at College Park, MD 20742.
E. Geraniotis is with the Department of Electrical Engineering and the Systems Research Systems, University of Maryland at College Park, MD 20742.
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SEQUENTIAL TESTS FOR MEMORYLESS DISCRIMINATION FROM DEPENDENT OBSERVATIONS--PART I: OPTIMAL TESTS

Evaggelos Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD 20742

ABSTRACT

The problem of sequential discrimination between two dependent sequences of observations is addressed. The discrimination problem is modeled by means of a general sequential binary hypothesis test, the main emphasis being on situations that cannot be modeled as signals in additive noise. The dependence in the stationary observation sequences is characterized by m-dependent, ϕ-mixing, α-mixing, or ρ-mixing conditions. Part I of this two-part study is concerned with asymptotically efficient sequential discrimination when the statistics of the observation sequences are known. We consider decision tests according to which the observations X_i, $i = 1, 2, ..., n$, are passed through a memoryless nonlinearity $g(\cdot)$ and summed up to form the n-th step test statistic $T_n = \sum_{i=1}^{n} g(X_i)$. This is processed further to provide either (i) linear tests of the form $S_n = \bar{A}T_n + \bar{B}n$ or (ii) quadratic tests of the form $S_n = \frac{1}{n}AT_n^2 + BT_n + Cn + D$. Finally, S_n is compared to an upper and a lower threshold and the procedure terminates or continues to step $n+1$ as in the usual sequential probability ratio tests (SPRTs). The coefficients $\bar{A}$ and $\bar{B}$ of the linear test are selected so that the normalized drifts of S_n are antipodal under the two hypotheses; $\bar{A}$ and $\bar{B}$ are related to the asymptotic means $\mu_i = \lim_{n\to\infty} n^{-1}E_i\{T_n\}$ and variances $\sigma_i^2 = \lim_{n\to\infty} n^{-1}Var_i\{T_n\}$ of T_n under hypothesis H_i, $i = 0, 1$. The coefficients A, B, C, and D of the quadratic test are selected so that the statistic becomes asymptotically equivalent to the likelihood ratio statistic; these coefficients are also related to μ_i's and σ_i^2's. The nonlinearities g are chosen to minimize the expected sample sizes under the two hypotheses of the sequential tests described above subject to the constraint that the error probabilities remain smaller than some prespecified values. The optimal such nonlinearities are obtained as solutions to linear or nonlinear integral equations involving the marginal and bivariate pdfs of the observations. The performance of the various sequential tests and nonlinearities is compared via simulation for situations of practical interest encountered in radar discrimination and the advantage of using our tests and nonlinearities over the sequential test employing the i.i.d. nonlinearity is demonstrated. Part II of this study treats the problem of robust sequential discrimination from observation sequences with statistical uncertainty.

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ROBUST SEQUENTIAL TESTS FOR MEMORYLESS DISCRIMINATION FROM DEPENDENT OBSERVATIONS

Evaggelos Geraniotis

Department of Electrical Engineering
and Systems Research Center
University of Maryland
College Park, MD 20742

ABSTRACT

The problem of robust sequential discrimination from two dependent observation sequences with uncertain statistics is addressed. As in Part I ([1]) of this study, which treated asymptotically optimal sequential discrimination for stationary observations characterized by m-dependent or mixing type of dependence, sequential tests based on memoryless nonlinearities are employed. In particular, the sequential tests robustified in this paper employ linear test statistics of the form $S_n = \bar{A}\sum_{i=1}^{n} g(X_i) + \bar{B}n$, where $\{X_i\}_{i=1}^{n}$ is the observation sequence, the coefficients $\bar{A}$ and $\bar{B}$ are selected so that the normalized drifts of S_n are antipodal under the two hypotheses, and the nonlinearity g solves a linear integral equation. As shown in Part I, the performance of these tests is very close to that of the asymptotically optimal memoryless sequential tests when the statistics of the observations are known. The above tests are robustified in terms of the error probabilities and the expected sample numbers under the two hypotheses, for statistical uncertainty determined by 2-alternating capacity classes for the marginal (univariate) pdfs and upper bounds on the correlation coefficients of time-shifts of the observations sequence for the bivariate pdfs. Finally, the robustification of sequential tests based on a test statistic similar to S_n defined above is carried out for detecting a weak-signal in stationary m-dependent or mixing noise with uncertainty in the univariate and bivariate pdfs.

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NEURAL NETWORKS FOR SEQUENTIAL DISCRIMINATION OF RADAR TARGETS

J. A. Haimerl and E. Geraniotis

Abstract

In this paper, perceptron neural networks are applied to the problem of discriminating between two classes of radar returns. The perceptron neural networks are used as nonlinearities in two threshold sequential discriminators which act upon samples of the radar return. The test statistic compared to the thresholds is of the form $T_n(\mathbf{Z}) = \sum_{j=1}^{n-K+1} \gamma(Z_j, Z_{j+1}, \ldots, Z_{j+K-1})$ where Z_i, $i = 1, 2, 3, \ldots$ are the radar samples and $\gamma()$ is the nonlinearity formed by the neural network. Numerical results are presented and compared to existing discrimination schemes.

Dr. Geraniotis is with the Department of Electrical Engineering and the Systems Research Center of the University of Maryland, College Park, MD 20742.
Joseph A. Haimerl was a Naval Research Laboratory/Systems Research Center Fellow at the University of Maryland; he is now with GE Aerospace, Government Electronic Systems Division, Moorestown, NJ 08057.
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SIGNAL DETECTION GAMES WITH POWER CONSTRAINTS

Doug Sauder and Evaggelos Geraniotis

ABSTRACT

In this paper we formulate mathematically and solve maximin and minimax detection problems for signals with power constraints. These problems arise whenever it is necessary to distinguish between a genuine signal and a spurious one designed by an adversary with the principal goal of deceiving the detector. The spurious (or deceptive) signal is usually subject to certain constraints, such as limited power, which preclude it from replicating the genuine signal exactly.

The detection problem is formulated as a zero-sum game involving two players: the detector designer and the deceptive signal designer. The payoff is the probability of error of the detector which the detector designer tries to minimize and the deceptive signal designer to maximize. For this detection game, saddle point solutions—whenever possible—or otherwise maximin and minimax solutions are derived under three distinct constraints on the deceptive signal power; these distinct constraints involves lower bounds on (i) the peak power, (ii) the probabilistic average power, and (iii) the time average power. The cases of i.i.d. and correlated signals are both considered.

D. Sauder is with Locus, Inc, Alexandria Virginia, VA. and the Department of Electrical Engineering University of Maryland, College Park, MD.

E. Geraniotis is the Department of Electrical Engineering and the Systems Research Center, University of Maryland, College Park, MD 20742

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Sequential Detection of Unknown Frequency-Hopped Waveforms

WILLIAM E. SNELLING AND EVAGGELOS GERANIOTIS, SENIOR MEMBER, IEEE

Abstract—The channelized receiver, which is optimal for the detection of unknown noncoherent frequency-hopped waveforms, bases its decision on a fixed-length block of input data. In this paper we present a sequential method of interception according to which, whenever a new data element is collected, a decision is made as to the presence or nonpresence of a frequency-hopped waveform. If that decision was indeterminate, another data element is collected. An optimal sequential test is derived, under the assumption that the waveform signal-to-noise ratio (S/N) is known. It is shown that this sequential test requires less data, on average, than the fixed length method to make a decision with the same reliability.

A truncated sequential test is also derived where a decision is forced, if still indeterminate, after some fixed amount of data is collected. The truncated test is shown to improve the number of samples needed for a decision when the input signal-to-noise ratio differs greatly from that assumed in the derivation of the test. Furthermore, it is shown that the truncated test yields a limited degree of robustness when the input S/N differs from that assumed. A detailed analysis of the performance of these tests is conducted from which a method for finding an optimal truncation point follows. Numerical results which are based on this analysis, as well as on simulation of the interceptor's performance, are presented to prove the preceding statements.

I. Background and Introduction

The first task in the interception of Spread Spectrum (SS) communications is the detection of the presence or nonpresence of the SS waveform to be intercepted. The detection of the SS waveform is a prelude to other interception processes such as feature detection, channel tracking, and message extraction. As a new development toward the detection problem, this paper applies and extends previously published results in sequential detection to the problem of the optimal detection of noncoherent Frequency-Hopped (FH) waveforms. By using likelihood function methods, the problem was previously solved in [2] for the case of an FH waveform with a known signal-to-noise ratio (SNR) and epochs with known starting times and durations. However, in that approach, the decision was based on a data segment of fixed size. Here, a sequential approach is taken, meaning that whenever a new data element is collected, a decision is attempted as to the presence or nonpresence of an FH waveform. If no decision is reached, another data element is collected.

The sequential approach to detection has a rich history. For the binary hypothesis problem with discrete-time independent identically distributed (i.i.d.) data, Wald [3] has derived the optimal sequential test. This test is optimal in the sense that no other test can reach a decision of the same Neyman–Pearson reliability within a smaller average time. This result has been extended to continuous time data in [4] and [5]. Others have suggested tests that must make a decision within a prescribed time. These are the "truncated" tests given in [6]–[8]. Truncation is desirable not only for implementation reasons but to improve the performance of a sequential test when the input statistics differ from those assumed in designing the test. In particular, Tantaratana and Poor [7] derived a truncated sequential test for i.i.d. Gaussian data with an unknown mean, which forms the foundation for the results included in this paper.

The process of development of the sequential test is begun by defining the observations model for a composite hypothesis problem. Specifically, given the observation $y(t)$, the problem is one of choosing between H_0, which is the hypothesis that an FH waveform is not present, and $H_{\gamma'}$, which is the hypothesis that an FH waveform is present with an SNR γ' where $0 < \gamma'$. The model is precisely

$$H_0:\ y(t) = \tilde{n}(t)$$

versus

$$H_{\gamma'}:\ y(t) = \sum_{i=1}^{N_h} x_i(t) + n(t) \qquad 0 < \gamma' \tag{1}$$

where

- $x_i(t)$ equals $\sqrt{2S'} \sin(\omega_{k_i} t + \theta_i)$ for $iT_h \le t \le (i+1)T_h$.
- $n(t)$ is white Gaussian noise with two sided spectral density $N_0/2$.
- ω_{k_i} for $1 \le k_i \le K$, is one of a family of known frequencies within the spread spectrum bandwidth with these being uniformly random for each epoch.
- θ_i is random phase with uniform distribution.
- S' is the average signal energy.
- T_h is the epoch, or time duration, of each hop.
- N_h is the number of hops over message duration.

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W. E. Snelling is with the Johns Hopkins University, Applied Physics Laboratory, Johns Hopkins Rd., Laurel, MD 20707, and the Department of Electrical Engineering, University of Maryland, College Park, MD 20742.

E. Geraniotis is with the Department of Electrical Engineering and the Systems Research Center, University of Maryland, College Park, MD 20742.

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Presence Detection of Binary-Phase-Shift-Keyed and Direct-Sequence Spread-Spectrum Signals Using a Prefilter-Delay-and-Multiply Device

JOHN F. KUEHLS, MEMBER, IEEE, AND EVAGGELOS GERANIOTIS, SENIOR MEMBER, IEEE

***Abstract*—The specific problem of detecting the presence of either binary-phase-shift-keyed (BPSK) signals or BPSK direct-sequence spread-spectrum (DS/SS) signals with a prefilter-delay-and-multiply (PFDM) device is considered. Using stationary process theory and Fourier analysis, the optimum PFDM structures for signal presence detection of BPSK signals with known bit rates and carrier frequencies, and BPSK DS/SS signals with known chip rates and carriers, in additive colored Gaussian noise are derived. The structures are optimum in the sense that they maximize the spectral signal-to-noise ratio (SNR) of an output periodic waveform which has fundamental frequency equal to the bit or chip rate of the signal. Two of the optimum structures that are derived and analyzed herein are the optimal prefilter-square device, and the optimal PFDM with delay set to one-half of the signal's bit or chip duration *T*. The latter structure has not been reported as of yet, and it is significant because it specifies the optimum prefilter for a *T*/2 delay-and-multiply detector.**

Exploiting a general expression for the output spectral SNR that was needed to derive the optimal structures for known bit or chip rates, a robust structure for the presence detection of BPSK or BPSK DS/SS signals with unknown bit or chip rates is also found. Finally, the spectral SNR is related to true performance measures when probabilities of detection and false alarm for both known and unknown bit or chip rates are derived, and the tradeoffs between SNR, length of observation interval, and time or bandwidth mismatch are studied. Additionally, the detection probability for an optimal PFDM is compared to that for a standard ad hoc configuration.

I. Introduction

How does one detect the presence (presence detection differs from what is usually called detection in that a presence detector only seeks to determine whether or not a signal is on the air, whereas the usual detector seeks to determine the transmitted message) of a signal in Gaussian noise? Standard techniques are available, and for one class of signals—the known signal—they are well established. A known signal may be detected by either passing the received waveform through a filter matched to the signal, or by correlating the received waveform with a reference that is proportional to the signal. These approaches are equivalent mathematically and optimum (follow from the likelihood ratio test) when the additive Gaussian noise is white (AWGN) [1]. When the signal is not known, the matched filter/correlator approach is not particularly useful because it requires knowledge of the signal. With regard to signal presence detection, any digitally modulated signal cannot be considered known unless the sequence which modulates the signal is known. Matched filters/correlators cannot therefore be used to detect the presence of a binary-phase-shift-keyed (BPSK) signal unless the underlying message sequence, which shifts the phase, is known. BPSK direct-sequence spread-spectrum signals are BPSK signals with a pseudonoise (PN) spreading sequence overlaying the message sequence; hence, matched filters/correlators cannot be used to presence detect BPSK DS/SS signals unless the PN spreading sequence is known.

Because of the random nature of the sequence which shifts their phase, BPSK signals are not periodic; hence, they have continuous Fourier spectra (DS/SS signals have a *pseudocontinuous* spectrum—spectral lines separated in frequency by the reciprocal of the duration of the PN sequence). This, consequently, makes them difficult to detect using a conventional analog spectrum analyzer or Fast Fourier Transform (FFT) [2], which are the optimal devices for detecting unknown signals that have discrete spectra in AWGN [1]. It is known, however, that when certain nonlinear operations are applied to BPSK-signals, discrete spectral components arise. These components are then often detectable using spectrum analyzer/FFT techniques. A nonlinear operation can thus serve to map BPSK signal presence detection from the detection of an unknown continuous-spectrum signal to the detection of a discrete-spectrum signal (with known or unknown spectral line frequencies, depending upon the extent of *a priori* knowledge of the BPSK signal's parameters).

In practical systems currently used for the detection of BPSK signals, nonlinear operations are employed. In general, the nonlinearity is quadratic, as is the case with the delay-and-multiply detector, which will be discussed in this work. Another feature that characterizes these nonlinear transformations is that they are typically ad hoc. Little has been done with regards to determining optimal transformations. The work of Gardner [3], [4], however, has provided some insight. He has applied the theory of *cyclostationary* processes [5], exploiting the *spectral correlation* [6] properties of PSK signals to determine *locally*

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J. F. Kuehls is with the Department of Defense, Fort Meade, MD, and George Washington University, Washington, DC.
E. Geraniotis is with the Department of Electrical Engineering and Systems Research Center, University of Maryland, College Park, MD 20742.
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Adaptive Multichannel Detection of Frequency-Hopping Signals

Larry W. Nemsick, *Member, IEEE*, and Evaggelos Geraniotis, *Senior Member, IEEE*

Abstract—This paper presents an adaptive multichannel radiometer designed to detect frequency-hopping (FH) signals in complex signal environments. This is accomplished by having each channel update its hop threshold to reflect the current environment and excise any persistent hop activity inconsistent with an FH signal from subsequent processing. This strategy allows the receiver to discriminate FH signals from any random noise or interference activity with relatively small degradations as compared to operation in stationary additive white Gaussian noise. This robust performance contrast that of non-adaptive receivers presented in previous studies, which are susceptible to all sources of inband transmissions and can be overwhelmed in many environments.

Two data collection schemes are considered for the proposed receiver, both of which attempt overall decisions using fixed-length blocks of data. In the first scheme, denoted as block detection, successive decisions are based on consecutive, nonoverlapping blocks of data, while in the second, denoted as block-sequential detection, decisions are made each time a new datum is collected. The block-sequential scheme is shown to offer greatly reduced average signal detection times and, thus, is the preferred approach.

I. Introduction and Background

Signal detection is a hypothesis testing process involved with determining whether a specific radio frequency (RF) signal is present. The test can be formulated as

$$\begin{aligned} H_0:\ & r(t) = n(t) \qquad 0 \le t \le T \\ H_1:\ & r(t) = s(t) + n(t) \end{aligned} \tag{1}$$

where $s(t)$ is the target signal and $n(t)$ the background environment. The object is to observe $r(t)$ over the time interval $[0, T]$ and decide which alternative is true. A successful detection is a prelude to other tasks, such as identification, geolocation, and intelligence extraction.

The approaches to signal detection are generally based on radiometry. Both wideband and multichannel radiometers have been widely applied to the detection of frequency hopping (FH) signals (see [1]–[5], [8]), with the latter achieving optimum or near-optimum performance depending on the implementation. However, these conventional approaches will respond to any signal activity in their overall detection bandwidths and, consequently, can be overwhelmed due to their inability to discriminate FH signals from any noise or interference activity. Hence, it is desirable to construct a receiver which exploits the known structure of FH signals via a channelized front-end, while offering the robust detection capability necessary for operation in complex signal environments.

This paper extends previous studies on signal detection by constructing an adaptive multichannel radiometer where each channel updates its hop threshold to reflect the current environment and excises any persistent activity inconsistent with an FH signal from further processing. This strategy is designed to discriminate FH signals from any noise or interference activity with relatively small performance degradations as compared to operation in stationary additive white Gaussian noise (AWGN). In addition to this robust detection capability, the proposed receiver is also designed to maintain the same near-optimum performance achieved by a conventional filter bank combiner (FBC) implementation in stationary AWGN.

Two data collection schemes are considered for the proposed receiver. In the first scheme, denoted as block detection, the receiver makes successive overall decisions using data elements (e.g., hop-by-hop energy measurements) collected over consecutive, nonoverlapping intervals spanning T seconds each. In the second scheme, denoted as block-sequential detection, overall decisions are still based on fixed-length blocks of data, except that decisions are now made each time a new datum is collected using data spanning the most recent T seconds. This results in successive overall decision with all but two data elements in common. The second data collection scheme, which is also known as binary moving window detection (see [5]–[6]), is designed to offer greatly reduced average signal detection times, as compared to the block scheme.

This paper is organized as follows. The detection of FH signals with an adaptive multichannel radiometer employing block and block-sequential detection is addressed in Sections II and III. Expressions for false alarm and detection performance are developed for each approach in terms of the received signal strength. The receivers are assumed to have perfect time and frequency alignment to the target signal in these sections. The impact of removing this assumption is addressed in Section IV. Hypothetical examples illustrating the performance of each approach are included in Section V. These examples substantiate the above statements on the superior performance of the adaptive multichannel radiometer and the block-sequential scheme.

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L. W. Nemsick is with The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723.

E. Geraniotis is with the Department of Electrical Engineering and the Systems Research Center, University of Maryland, College Park, MD 20742.

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ANALYSIS OF COMPRESSIVE RECEIVERS FOR THE OPTIMAL INTERCEPTION OF FREQUENCY-HOPPED WAVEFORMS

William E. Snelling [1] and Evaggelos Geraniotis [2]

ABSTRACT

This paper establishes that the compressive receiver is a practical interceptor of high performance. Given a signal of a particular duration, a compressive receiver can estimate simultaneously all frequency components within a set wide band. This processing is similar to a parallel bank of narrowband filters, which is the optimal detector of frequency-hopped signals. Furthermore, hop frequency is estimated to yield performance equal to the parallel filter configuration. We assume interference to be stationary, colored Gaussian noise and present a model of the compressive receiver that contains all its salient features. Locally optimal detection is achieved by taking the compressive receiver output as an observation and applying likelihood ratio theory at small signal-to-noise ratios. For small signals, this approach guarantees the largest probability of correct detection for a given probability of false alarm and thus provides a reference, to which simplified or ad hoc schemes can be compared. Since the locally optimal detector has an unwieldy structure, a simplified suboptimal detector structure is developed that consists of simple filter followed by a sampler and a square-envelope detector. Several candidates for the filter's response are presented. The performance of the locally optimal detector based on compressive receiver observations is compared to the optimal filter-bank detector based on direct observations, thus showing the exact loss incurred when a compressive receiver is used. The performance of various simplified schemes based on compressive receiver observations is analyzed and compared with that of the locally optimal detector.

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[1]Dr. W. E. Snelling is with The Johns Hopkins University Applied Physics Laboratory, Johns Hopkins Road, Laurel, MD 20723.

[2]Dr. E. Geraniotis is with the Department of Electrical Engineering and the Systems Research Center, University of Maryland, College Park, MD 20742.

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THE INTERCEPTION OF SPREAD SPECTRUM WAVEFORMS WITH THE AMPLITUDE DISTRIBUTION FUNCTION

William E. Snelling [1] and Evaggelos Geraniotis [2 3]

ABSTRACT

Within the research effort related to unfriendly detection and interception of secure communications, an innovative concept called the Amplitude Distribution Function (ADF) is used to construct a detector that is an enhancement to the radiometer. The ADF is introduced and shown to be roughly the average probability distribution of a random process. The significance of ADF in the is that, under most spreading modulations, e.g. phase and frequency, the ADF is invariant. This suggests that a detector built around the ADF idea would be robust and of general purpose.

To develop the ADF methodology, a mathematical foundation is laid consisting of a sequence of definitions, lemmas, and theorems, an outline of which is included in the paper. The most significant result is that the ADF of signal plus noise is the convolution of the ADF of signal and the ADF of noise taken separately. These ideas are applicable through the definition of the Amplitude Moment Statistic (AMS), a statistical transform that converges to the moment generating function of the ADF. Hence, the AMS is the vehicle for indirectly estimating the ADF from observations. For the particular problem of detecting a modulated sinusoid in stationary Gaussian noise, a detector is developed around the AMS. The detector's performance is analyzed, compared with that of a radiometer, and shown superior for small (≈ 10) time-bandwidth products.

[1] William E. Snelling is with The Johns Hopkins University Applied Physics Laboratory, Johns Hopkins Road, Laurel, MD 20723.

[2] Evaggelos Geraniotis is with the Department of Electrical Engineering and the Systems Research Center, University of Maryland, College Park, MD 20742.

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MEMORYLESS LOCALLY OPTIMUM DETECTION OF CHIP RATE LINES OF DS/SS SIGNALS

John F. Kuehls and Evaggelos Geraniotis

Abstract

Assuming that a binary phase-shift-keyed (BPSK) direct-sequence spread-spectrum (DS/SS) modulated signal (or a narrowband BPSK signal) plus Gaussian noise is input to a delay-and-multiply or squarer, a memoryless locally optimum scheme for detecting the generated rate line is introduced. The locally optimum formulation is used because the rate line is a signal in non-Gaussian noise, and it is typically weak. It is shown that the scheme employing the memoryless locally optimum nonlinearity outperforms the standard delay-and-multiply or squarer devices by a wide margin.

J. F. Kuehls is with ESL Inc., Maryland Engineering Lab, Columbia, MD 21046.

E. Geraniotis is with the Department of Electrical Engineering and the Systems Research Center, University of Maryland, College Park, MD 20742.